

**DEVELOPING POLICY FOR BENEFICIAL USE OF WASTE HEAT ENERGY  
FOR LOW-CARBON IMPACT THERMAL DESALINATION**

by  
Gregory Stephen Knoop, R.A., LEED AP

A capstone submitted to Johns Hopkins University in conformity with the requirements  
for the degree of Masters of Science Energy Policy and Climate

Baltimore, Maryland  
December 2017

© 2017 Gregory Stephen Knoop  
All Rights Reserved

## **Abstract**

This study proposes that policy—supported by innovative technologies in desalination and cogeneration—can be used as a mechanism to facilitate thermal desalination for the relief of water stress without the burden of additional carbon emissions. The research methodology for this study drew from technical journals, trade publications, academic research papers, and government publications. The research investigated global water stress, state of the industry desalination methods, industrial combined heat and power (cogeneration) technologies, and existing policies to find viable intersections that support the thesis. Each part of the study synthesizes resulting potentials that are then wrapped together in the policy section regarding the use of policy to support the beneficial use of waste heat energy for low carbon impact thermal desalination. The conclusion of the study integrates the entire picture of market conditions, technologies, and policies to suggest a vision forward.

## **Acknowledgements**

The author would like to acknowledge and give special thanks to Capstone advisor Charles M. Clay, P.E., EMBA, MCHA, BSME, C. Build.E, FCABE, CHFM and Capstone professor and advisor Daniel S. Zachary, Ph.D.

## **List of Tables**

- Table 1: EIA Table: “Estimated LCOE (simple average of regional values) for new generation resources, for plants entering service in 2022” (Figure limited to selected technologies)
- Table 2: Almar Water Solutions O&M Costs in MENA Desalination plants
- Table 3: Almar Water Solutions Cost of Water per meter square in MENA Desalination plants

## **List of Figures**

- Figure 1: Water Stress Around the World
- Figure 2: Population Density Around the World
- Figure 3: Diagram of U.S. energy waste and use 2016
- Figure 4: Current California Water Compact distributions 2017
- Figure 5: Thermal Desalination: How It Works
- Figure 6: MED Plant Diagram
- Figure 7: MSF Plant Diagram
- Figure 8: Filtration Desalination Reverse Osmosis: How It Works
- Figure 9: Reverse Osmosis Plant Diagram
- Figure 10: Coal Fired Power Plant Diagram
- Figure 11: Combined Cycle Gas Turbine Power Plant Diagram
- Figure 12: Nuclear Power Plant Diagram
- Figure 13: Concentrated Solar Thermal Power Plant Diagram
- Figure 14: Cogeneration Power Plants and Thermal Desalination
- Figure 15: Map Israeli - Jordanian Desalination and Pipeline Master Plan

Notes on Figures—In this study, the author has diagrammatically illustrated multiple power plants, desalination processes, desalination plants, and cogeneration plants. No external attribution is given to these illustrations other than to the illustrator. While the illustrations are original, the processes and configurations can be found in and were inspired by multiple sources, and this study makes no claim to the originality of these concepts.

## **Introduction**

### **Thesis and Statement of Purpose**

Water, heat, energy, waste, policy: The purpose of this study is to find the intersection of these five points. This study proposes that policy— supported by innovative technologies in desalination and cogeneration—can be used as a mechanism to facilitate desalination for the relief of water stress without the burden of additional carbon emissions.

The study will look at the conditions of water stress in a few sample areas such as the Levant, the Indian subcontinent, the American southwest, and other places around the world. The global phenomenon of water stress and drinking water shortages arising from growing populations, poor resource management, and a changing climate have led to one of the greatest challenges as we continue on into the 21<sup>st</sup> century. One of many parts of the solution to water stress and reductions in resource availability the conversion of seawater to potable water through desalination to create additional supply from the vast resource of the world's oceans. Therefore, this study will also examine the various techniques for desalination and how they are implemented.

Many desalination processes use carbon-intensive energy. However, here we will explore other sources of thermal energy using cogeneration and zero-carbon processes that could be applied for thermal desalination. There are several great challenges in tapping the tremendous resource of brackish water from the seas for conversion to fresh water:

transportation and infrastructure, economic incentives, and master planning. In support of this study's thesis, there will be exploration of the many ways in which policy can create an incentivized societal mechanism to help relieve the growing human consumption of fresh water.

This study is broken into seven parts:

**Part 1: Worldwide Demand for Fresh Water**—Review worldwide demand for fresh water, including types of water, water stress, water conflict, state of the climate, and growing water demand.

**Part 2: Industrial Waste Energy**—Examine waste heat and CO<sub>2</sub> emissions to explore the potential for an untapped use of thermal energy.

**Part 3: Water Stress and Water Demand**—Look at water stress and water demand as driving a marketplace for new sources of fresh water.

**Part 4: Desalination Technologies**—Review the many types of thermal and filtration based desalination processes. This includes some analysis of where these technologies are used and what are some of the cost considerations that are relevant to reduced carbon and reduced energy waste.

**Part 5: Cogeneration Opportunities for Power Generation and Industrial Process—**

Explore cogeneration opportunities for power generation and industrial process specifically with respect to the use of waste heat energy in desalination as a means to have reduced total carbon emissions.

**Part 6: Policy—**Examine policy. This section explores the kinds of policy have existed to create market incentives for desalination and cogeneration. In addition, this section looks at the need for policy in infrastructure planning and the spending of public monies to support cogeneration, desalination, and the movement of industrially created fresh water. This section looks at a few case examples of effective policy for water management that has facilitated innovative changes and suggests the direction for policy surrounding desalination through cogeneration for reducing carbon impact and creating both adaptation and mitigation of raising fresh water demand and global warming trends.

**Part 7: Conclusion—**Present the conclusion where the study draws together market conditions, technologies, and policies to suggest a vision forward.



## **Part 1 – Worldwide Demand for Fresh Water**

### **The Challenge of Water Stress**

Fostering the recovery and management of fresh water supply is an imperative for the peoples of the world. We are heading into dangerous waters as the custodians of this planet and its fragile ecosystems. As the human population continues to grow and water demand continues to parallel that growth, there is an increasing danger that without intervention we may approach an existential cliff. According to a NASA study of 37 of the most significant aquifers that supply more than 35 percent of the of the world's fresh water source for human use, measurement between 2003-13 showed these waters to be depleting at alarming rates that will increase water stress, pose national security risks to many nations, and potentially lead conflicts.<sup>1</sup> Water resource management involves both the reduction of demand through conservation and the enhancement of supplies through desalination and associated infrastructure. It is this latter subject that this study will focus, although it fully recognizes that it is an integrative approach of both enhancing supplies and conservation to reduce demand that will lead to eventual solutions to restore balance. As the human population approaches 9 billion by 2050, we may also be approaching a fresh water crisis with catastrophic outcomes if we do not act to reduce water consumption and increase fresh water supply and recovery. Figure 2 shows a map of the density hotspots.

---

1. Richey, Thomas, Reager, Familglietti, Voss, Senson, and Todell, "Quantifying Renewable Groundwater Stress with GRACE", Page 5220

United Nations Secretary-General Ban Ki-moon stated, “The need for coordination in water management is especially compelling for the more than 260 international rivers and at least that many trans-boundary aquifers...,” and further noted, “...Access to water can exacerbate communal tensions.” He concluded that, “Despite these serious challenges, we must also recognize the potential for cooperation around shared water resources.” He called for investment in water security to ensure long-term international peace and security.<sup>2</sup>

It is essential to security, survival, and to life-sustaining balance on the planet to address our growing freshwater crisis by designing policy that will create the incentive mechanisms in the marketplace, including infrastructure and governance, to deploy cogeneration combinations of power generation and desalination technologies to restore and manage our water resources.

Figure 1 shows a map developed by the World Resources Institute shows the areas around the planet and the levels of water stress. When comparing areas of water stress with the population density shown in Figure 2 it shows that population can be a driver of water stress even in areas and regions where climatically there is expected water abundance. This will press the need for comprehensive water management policy to create new water supply and infrastructure where population growth has overwhelmed the capacity of natural replenishment. Although in the United States we are used to news reports about the water stress in the southwestern states, especially in California, the

---

2. UN Staff, “Water resources ‘a reason for cooperation, not conflict’, Ban tells Security Council”, *United Nations News Centre*, Page 1

maps show that even in the lush and green, water-rich northeast, there are growing red-zones that we can deduce are connected to the population density in Figure 2.

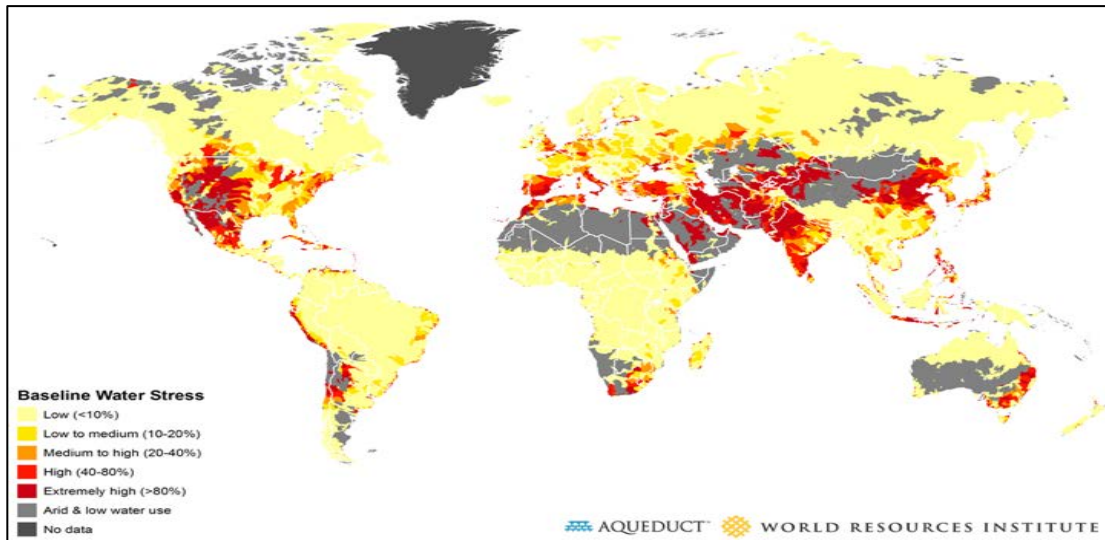


Figure 1 - Water Stress Around the World<sup>3</sup>

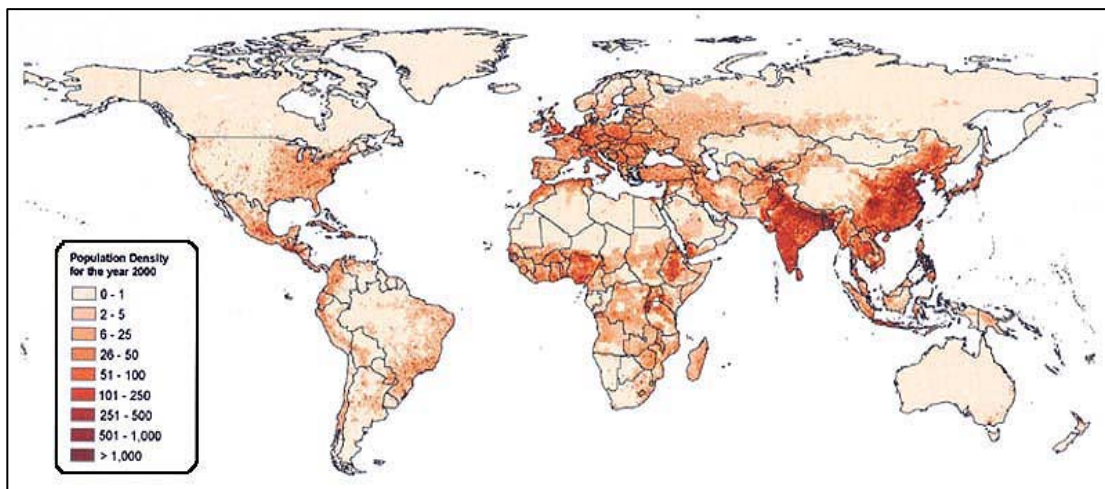


Figure 2 - Population Density Around the World<sup>4</sup>

<sup>3</sup> World Resources Institute, [www.wri.org](http://www.wri.org), 2017

<sup>4</sup> Center for International Earth Science Information Network (CIESIN), Columbia University and Centro Internacional de Agricultura Tropical (CIAT), <http://sedac.ciesin.columbia.edu>, New York, 2017

## **Current State of Water**

The oceans and waterways of the planet cover 70 percent of the surface area and thus, water is seemingly abundant. However, fresh water and potable water comprise only a fraction of the planet's water supply. Fresh water is approximately 3 percent of the total water on earth, and potable water is only 2.5 percent of the fresh water. These percentages make access to fresh and potable water much rarer. The demand for that potable supply has grown over the past century. To offset the demand, we must look for industrial processes to mitigate consumption.

## **Types of Water**

When we refer to the different types of water, it is helpful to see what industrial solutions for water extraction look like. Let's begin by looking at the chemical composition of different types of water solutions:

- Potable/drinking water total dissolved solids are under 500mg/l with variable chemical composition
- Fresh water total dissolved solids are up to 1,500mg/l with variable chemical composition
- Brackish water total dissolved solids range from 1,500-10,000mg/l with variable chemical composition
- Salt water has total dissolved solids of less than 10,000mg/l with variable chemical composition

- Seawater has a total dissolved solid ranging from 10,000-45,000mg/l with an average of about 35,000mg/l and with a more fixed chemical composition.<sup>5</sup>

These types of water show both the types of water that are acceptable for use in agriculture, human consumption, and other domestic uses, alongside the solutions that are considered unpalatable but potential sources for supply.

### **Growing Water Demand**

It is estimated that our world human population in 2017 of 7.6 billion people consumes 10 billion tons of fresh water every day through drinking, cleaning, agricultural cultivation, and industrial processes. If we look back just 100 years to 1917, the world had a population of 1.9 billion people. The simple human demand for water based on population growth has grown four times in just one century. In addition, our increased mobility, dietary habits, industrialization, and energy-intensive lifestyles have also contributed to growth in our demand and consumption of water, which has increased approximately 10 percent over the past century. While there may be arguments over climate issues with respect to water, population growth and modernizing lifestyles clearly increase the demand for water.<sup>6</sup>

“During the 20<sup>th</sup> century, the world population tripled, while water use for human purposes multiplied six-fold. The most obvious uses of water for people are as follows: drinking, cooking, bathing, cleaning, and—for some—watering family food plots. This domestic water use, though crucial, is only a small part of the total. Worldwide, industry

---

<sup>5</sup> Rezaei, Naserbeagi, Alahyarizade, and Aghaie “Economic evaluation of Qeshm island MED-desalination plant coupling with different energy sources including fossils and nuclear power plants”, Page 102

<sup>6</sup> World Water Council The Use of Water Today, Chapter 2

uses about twice as much water as households, mostly for cooling in the production of electricity. Far more water is needed to produce food and fiber (cereals, fruits, meat, cotton) and maintains the natural environment.”<sup>7</sup>

There is no sign that the trend reported in 2000 was slowed in any way over the past 17 years, especially with the past 15 years being the hottest years on record for our planet. With the massive increase in our populations and the massive draw of water increasing at double that rate, it is a demonstration of anthropogenic consumption growing at a rate that is increasing competition for supply, while we are witnessing changes in ecological sources like glaciers, great lakes, and aquifers that suggest the natural supplies are reducing while demand is increasing.

Water demand has been at the heart of conflicts such as the Arab-Israeli six-day war of 1967. This conflict involved more than 450,000 combatants from multiple nations. The U.S. Army in their 2008 water planning guide—*Potable Water Consumption Planning Factors by Environmental Region and Command Level*, Nov. 25, 2008—estimates that forces in climates like Israel consume a minimum of 11.17 gallons of water per capita, per day (but as high as 15.54 gallons/day).<sup>8</sup> This consumption rate is well above the approximate 1.3 gallons a day recommended for consumption for the average person. This is to say that conflicts for water are expensive in terms of water usage. Even a six-day conflict consumed 108 million man-days of drinking water dedicated to that conflict. The point here is that our planet’s human population is now consuming water at rates

---

<sup>7</sup> World Water Council The Use of Water Today, Chapter 2

<sup>8</sup> U.S. Army *Potable Water Consumption Planning Factors by Environmental Region and Command Level*, Page 1-8

never seen before in human history. Conflicts have arisen between nations to leverage access to natural sources of water. The cost measured in water use alone for a well-known conflict that spanned less than a week was unfathomably large and the sustained military presence and water use in that region is likely to have continued at equally alarming and unproductive levels. Creating engineered solutions that can be shared among neighboring states is likely to be a better value to the parties involved and might help facilitate peaceful coexistence as pointed out by Secretary-General Ban Ki-moon.

### **Reduced Water Supply**

The driving reason for this study is to seek solutions to a dwindling water supply. The planet's fresh water supply is approximately 3 percent of the  $326 \times 10^{15}$  gallons of water on the planet. This converts to  $1.32 \times 10^{15}$  tons of water on earth,  $3.9 \times 10^{13}$  of fresh water and  $1.17 \times 10^{12}$  of potable water. Humans are now using  $365 \times 10^9$  tons annually placing stresses on the natural replenishment cycle, which is only  $215 \times 10^9$  tons/year. This means there is a critical need for humans to reduce water consumption and/or enhance the replenishment of water industrially. There are two key issues adding to the consumption and stresses on fresh water: climate-driven changes in availability and anthropogenic driven changes in demand. Without attention to rebuilding water supplies and reducing demand to bring consumption back into balance with the supply and enhance the supply sources, our supply of potable water will run dry within a century. As noted in the earlier citation, the planet's aquifers are showing measurable reductions that give credence to the dangerous projections that our fresh water is running out faster than it can be replenished. Given that the depletion is being driven by measurable growth in human demand, this

drives the importance of human ingenuity to drive solutions. We will explore later cases of successfully achieving integrative solutions through water management.

### **Climate Driven Changes**

The earth's rising temperatures over the past two centuries have been recorded by a wide variety of sources. While there are some politically driven arguments regarding the reasons, the rising temperatures are generally accepted. In that context of rising global temperatures, we should expect this to impact our fresh water supplies. The temperature increases and extremes that have been at a level to ground air travel out of Arizona on extreme heat days are also the same temperature that will increase evaporation and contribute to droughts. The rising temperatures increase the rates of glacial melting that are visibly reducing a critical source of fresh water. Regardless of the reasons, the evidence of increasing stresses on water resources create growing need for solutions to meet the ravenous growth in human demand for this resource.

### **Anthropogenic Changes**

Reduced water supply can be clearly linked to human activities. In the past 200 years, the world has gone through industrial and technical revolutions. Human population has grown by 7.6 times, human development (especially in the coastal areas) has also increased significantly. Our technological maturation as a species has driven us to increased usage of water for a variety of purposes. We have used more water in the past 200 years than we had over the prior two millennia. Drawing from a variety of sources, we are aware that while water is greatly abundant on the planet's surface as it covers 70



percent of that area with the vast oceans of the world, only 2.5-3 percent of the earth's water is fresh water and 0.075-0.09 percent of all the water on earth is potable. Although it has been argued that the reducing resource from climate change and the warming of the planet may or may not have anthropogenic routes, it is inarguable that a growing human population with evolving technological and social lifestyles is using more of the resource. Energy demand continues to grow with the advancing lifestyles of the growing human population. The growth of the electrical grid and use of electricity have grown over the past century. In the early 20<sup>th</sup> century, the use and access of electricity by the world's population was negligible; in 2017 nearly 85 percent of the world has use and access of to electricity.<sup>9</sup> Much attention is given to the emergence of a variety of different systems to create electricity. Heat engines using a variety of fuel sources dominate as the prevailing electrical generation technology—whether they be coal, natural gas, biofuels, solid waste incineration, or nuclear. The common element of all these systems is the use of generated heat to turn steam turbines to generate electricity. In addition, all these systems reject large amounts of energy in the form of heat. This energy, which is now being wasted, could instead be harnessed.

---

<sup>9</sup> <https://data.worldbank.org>

## **Part 2 – Industrial Waste Energy**

### **Wasted Energy**

This study proposes that the significant amount of untapped waste heat energy can be used for more productive purposes through cogeneration. The modern industrialized world consumes resources such as hydrocarbon based fuels and water. The energy efficiency of these processes creates demonstrated levels of energy exhausted by design in the form of waste heat.

### **Industrial Waste and Power**

It is estimated that power plants in the US produce approximately 24.9 quadrillion Btu/yr.—much of it being waste heat energy. Industrial plants reject approximately 12.5 quadrillion Btu/yr. of wasted energy—also much of it in ejected heat. Petroleum refineries contribute another 22 quadrillion Btu/year to this wasted energy. The total amount of wasted energy in 2016 was more than 66 quadrillion Btu/year (Figure 3).<sup>10</sup> Again, much of this wasted energy is in heat ejection. In many of these processes, water is used at a coolant either through mechanized cooling towers or through heat exchanges with rivers, lakes, oceans, or other waterways. Waste heat is both a pollutant and an untapped resource. Any use of this energy would be without added CO<sub>2</sub>.

---

<sup>10</sup> Lawrence Livermore National Laboratory, LLNL.gov

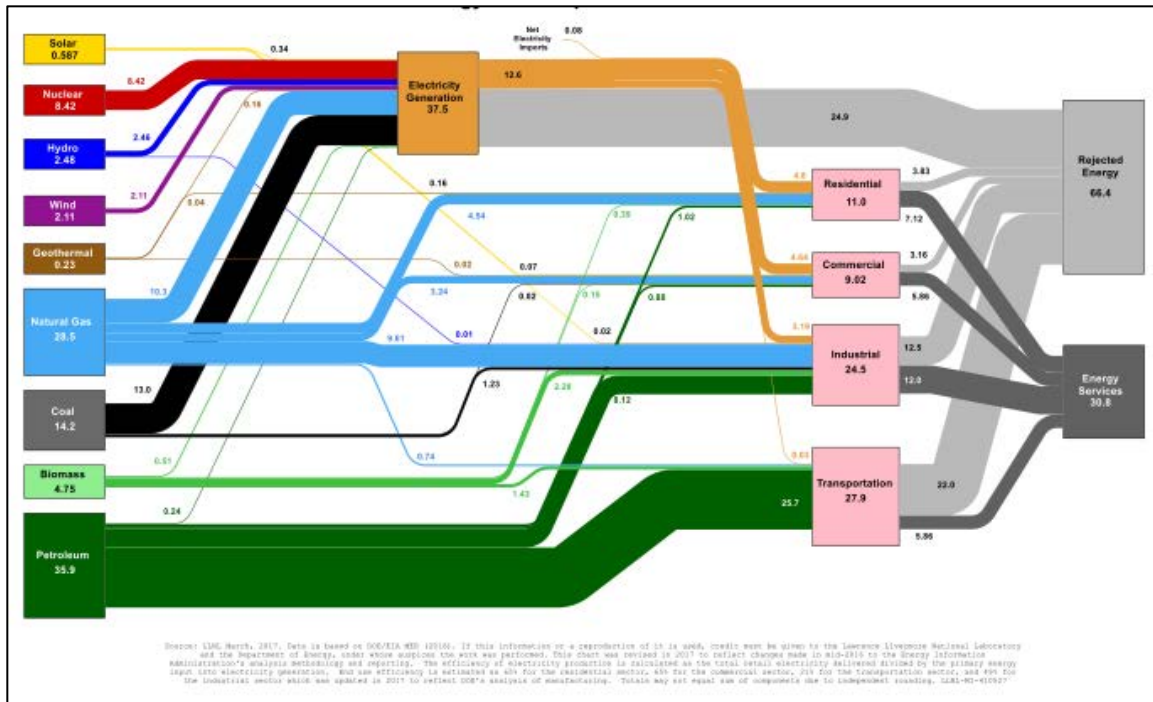


Figure 3 – Diagram of U.S. energy waste and use 2016<sup>11</sup>

## Industrial CO2

Through most of these heat and energy-intensive industrial plant processes, there is the presence of CO2 emissions and other GHG emissions. Furthermore, the industrial processes that use heat for desalination (non-cogeneration) also produce CO2 emissions and other pollutants (dependent on the fuel source).

## Lack of Resilient Secondary Water Supply Infrastructures

Human use of water for potable use, industrial use, and agriculture come from a variety of sources as follows:

<sup>11</sup> Lawrence Livermore National Laboratory, LLNL.gov

### **Natural/Non-Industrial Sources**

The natural sources for fresh water are river ways and streams, fresh water lakes and bays, aquifers, and precipitation. Generally, precipitation is part of the replenishment cycle for glacial source water, aquifers, and riparian sources—although precipitation also can be a significant source for agriculture. Well water is generally assumed to be a part of the natural sources of fresh water.

### **Industrial Sources**

There are several processes that involve traditional and contemporary technologies for creating fresh water. Storm water can be filtered and recycled. Desalination can be used to convert brackish salt water solution to fresh water in a variety of ways that will be addressed further in this study. Processing and treating waste water can also be performed.

### **CO<sub>2</sub> Emissions**

We don't want to take another key process and make it contribute more carbon than is needed. Desalination processes are energy intensive. Plants throughout the Middle East commonly use thermal desalination with the steam boiler processes that use fossil fuels. Filtration processes require energy to drive pumping pressures for filtration and pre-filtration. Unless driven from purely renewable sources, which most of the current processes are not, the desalination of seawater is energy intensive and therefore would have a significant carbon impact. As stated in the thesis, we must find the viable

intersections of carbon-neutral solutions driven by policies that create market incentives along with infrastructure to deliver industrial fresh water with minimal carbon emissions.

Are there zero-carbon and aquifer-neutral solutions? The answer just may be yes. By capturing energy already produced or by using renewable energy sources, we can look to desalination as an obvious strategic choice to mine fresh water from the vast sources of the world's oceans. To find solutions for water supplies that are carbon-neutral and do not draw from natural fresh water supplies, we should also look to industrial technologies that are either powered by renewable energy or technologies capable of drawing critical energy from wasted and rejected heat to facilitate the desalination process.

Under current economic and political conditions, there may be no motivation for doing something different than drilling wells and extracting from riparian sources. This is where we rely on policymakers to recognize the critical need for a shift in use of aquifers and current riparian water sources and begin requiring investment in distribution of industrially manufactured water that is aquifer-neutral and carbon-neutral.

## **Part 3 – Water Stress and Water Demand**

### **Water Stressed Areas**

Water stress can be incurred by numerous factors. The most obvious happens in areas of the world where desert conditions intersect a growing human population where the geography is increasingly hostile to sustaining living conditions. Although the natural response may be, don't live there, the realities of national territories, ethnic homelands, and restrictive borders, as well as economic inflexibilities, may hamper the ability of a group to just move along to better places. We also exist in a growingly crowded world. Humans are drawn to settle in areas with essential resources for survival. This tendency makes it possible that even the abundant parts of the world may at some time become water stressed. Examples of water stressed areas are found throughout North Africa, the Levant/Middle East, the Arabian Peninsula, and the Indian sub-continent.

There is increasing risk of water competition creating international conflicts. Both developing and industrialized nations have water usage that is driven by industrial agriculture, advanced power use, industry, and domestic use. This usage creates driving pressures to shape regional international policies around capturing increasing amounts of the resource. Many of these developing nations are in a race to adopt technologies and lifestyles of the more developed nations without assessing whether austerity or conservation might shape adoption of new technologies or methods to incorporate efficient water use for lower per-capita demand from the start. There is an increasing

threat that developing nations will continue to increase per-capita consumption at a rate that is greater than the population growth.

For example, the People's Republic of China invaded Tibet in 1950. This was a clear strategic move to capture control of the Tibetan plateau, which is the source water of a majority of East Asia. East Asia, with the two most populous nations in the world (China and India), is a part of the world where competition over natural fresh water sources will continue to be a critical challenge. China has engaged in significant water infrastructure projects to harvest the transnational rivers like the Mekong River. Downriver countries are facing changes in their supplies due to up river use by a stronger neighbor. A similar condition exists with the Brahmaputra River that travels across China and India before it heads to the sea in Bangladesh.

Israel, Jordan, Syria, and the Palestinian territories have been involved in ongoing competition. The region is considered one of the most water stressed areas in the world. Four nations have been competing for access and control of the fresh water sources of the River Jordan. This has led to several conflicts in the region, including for control over the Golan Heights, formerly controlled by Syria and currently controlled by Israel.

In the U.S., although the states are not in danger of conflicts, they do compete for water access. The Colorado River is one of these interstate rivers where seven states (Colorado, New Mexico, Utah, Wyoming, Nevada, Arizona, and California) share access. The Colorado River Compact was written in 1922 and enacted in 1929. It created the

framework for water allocations for each state. In addition, this Compact also developed the targets for transnational agreements with Mexico for their access to these waters and with the Indian nations whose lands also benefit from access to the river and tributaries. Water stress and the regular threat of drought are key factors in establishing agreed-to allowances and to managing sustainable flow. Though the Compact addresses access and use of the water, it does not address ecological or water quality, which are growing issues of concern. Seven states and a neighboring nation are dependent on a single river.<sup>12</sup>

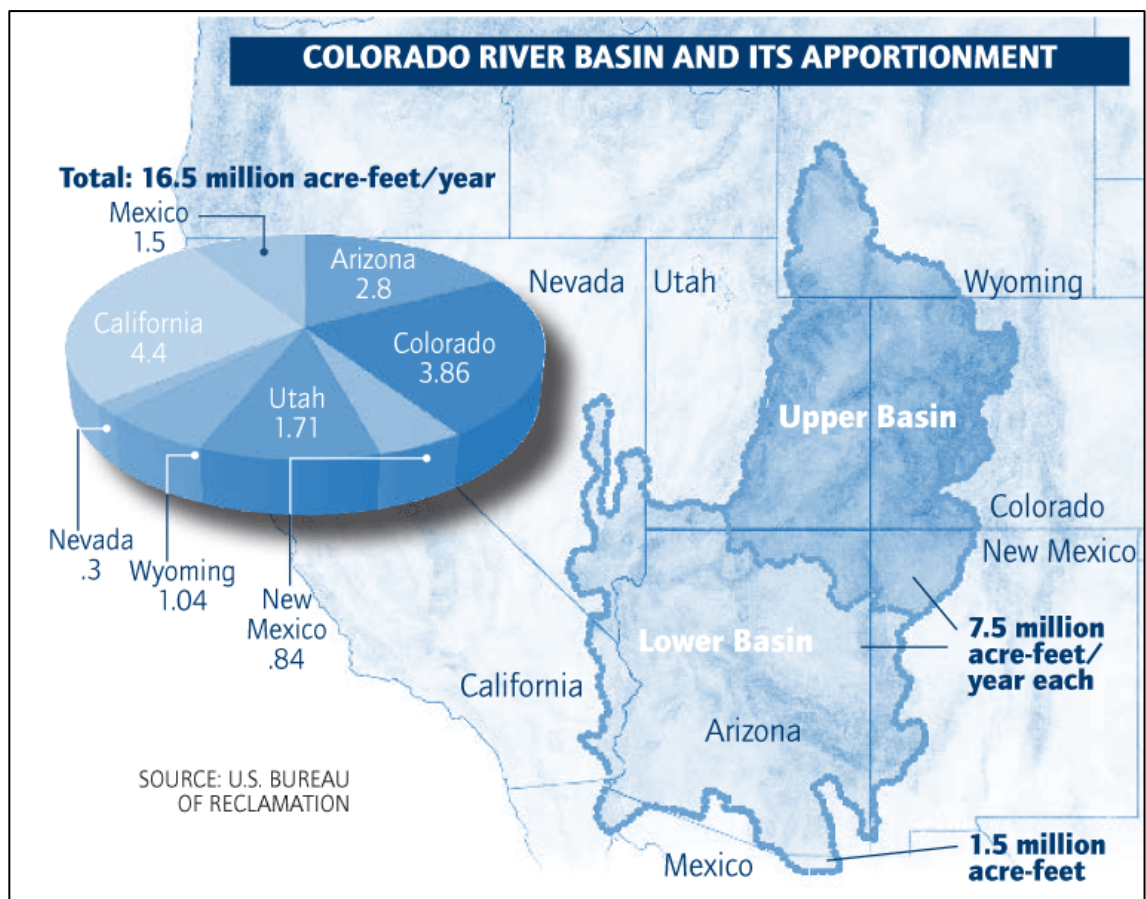


Figure 4 - Current California Water Compact distributions 2017<sup>13</sup>

<sup>12</sup> Crystal Thompson and CRWUA Staff, "Law of the River", [www.crwua.org](http://www.crwua.org).

<sup>13</sup> Matt Jenkins "The water czar who reshaped Colorado River politics", Page 1



Policy is the foundation of a cooperative sharing of the resource and may be the foundation for water sharing of industrially produced fresh water. Furthermore, globally driven trends continue to shape the ecological livelihoods of source waters of the Colorado River. The riparian development around this river and population growth in the region continues to shape the demand on the resource. Competition, even among cooperative states of the same nation, will propel the need for policy and market driven solutions to reduce potentials for conflict and/or critical stresses that can create economic and social instability. The US Department of the Interior performed an extensive study of supply and demand to create a vision forward. A number of demand management and conservation measures were addressed. For supply enhancement, the study marks targets for 2035 and 2060 the number one method listed was desalination that would capture water from the Gulf of California, the Pacific Ocean, the Salton Sea, and ground water in several of the states. With potentials to of up to 2,476,000 acre feet per year.<sup>14</sup> This points to policy and planning as a mechanism to leverage technologies for long range transformation.

### **Market Demand for Water**

China, Myanmar, Laos, Thailand, Vietnam, and Cambodia share the Mekong River, which is the seventh largest river in the world. Each of these countries has different and competing use of waters. Five of these countries are downstream of China, which leaves them with reduced access to the water flow that China controls. Although riparian treaties can be established, these smaller downstream countries are in a weak leverage point.

China, as the world's most populated country, has nearly 20 percent of the world's

---

<sup>14</sup> US Department of the Interior "Colorado River Basin Supply and Demand Study", US Department of the Interior, Washington DC, 2012, Page 13

population and one of the fastest growing economies, with multifaceted needs for water. China is a diverse economy with water use in agriculture, industry, and domestic applications. However, the country only has access to approximately 7 percent of the world's fresh water supply. Access to water has shaped China's international policy, including the annexation of Tibet to control the Tibetan plateau, giving China control over the region's water supply.

### **Market Driven Pricing**

Fresh water access exists in the marketplace. For example, in the U.S., we are used to seeing water and sewage costs on our monthly utility bills or on our bottled water from the grocery shelf. The price is driven by the availability of the resource, the costs of the infrastructure, and the demand. "The socially optimal water allocation is one whereby the net output of a region is maximized and is often conceptualized as the choice of a benevolent social planner. In economics, the social optimum is termed 'Pareto efficient,' an allocation of resources (including compensating transfers of money) such that no person can be made better off without making someone else worse off. A third way of conceptualizing the social optimum is a situation in which all welfare increasing trades and technology choices are implemented. The central economic result is that the marginal values of water across all uses are equated. Economists call the social optimum 'efficient' because water is allocated to those who value it the most." <sup>15</sup>

---

<sup>15</sup> Howard Chung and David Sunding, "Water Markets and Trading", *The Scholarly Commons*, Cornell University School of Hotel Administration, New York, 2006, Page 241

## **Water Stress**

Water stress contributes to the fresh water economics in a profound way and is a simple matter of supply and demand. In Israel, Jordan, and the Palestinian Territories, the demand for water has played a significant role in the direction of these countries' economies and the development of their foreign policy.

## **Water Abundance**

Much of the U.S. would be considered water abundant. Do U.S. states owe water equity to those that don't have the same abundance? What are the interstate rules regarding access to and consumption of water? The concern may be that water abundance can possibly create a lack of initiative for many states without recognizing the imperative to join more visibly distressed regions in taking action. While Maryland may appear to have water abundance, consumption of subsurface aquifer based water for farming is actually causing the eastern portion of the state to sink and allowing for the seawater pressure to push higher salinity levels into the soils. There is more to be found when you look beneath the surface. This is to say that water abundance may be illusory, and the imperative for creating forward thinking, economically sensitive policies for water management, water conservation, and water restoration are an imperative that should be shared by all regions. This is where the Federal Government and international bodies play a role in establishing trans-boundary rules, whether on a national scale or international scale.

## **The Role of Government in Water Supply**

Israel is an example of the government playing a successful role in solving water stress.

Policy set forth a national priority to manage freshwater sources and introduce methods for conservation in the agricultural use of water. As Israel's population has grown and the economy has thrived, demand has increased. This growth in demand has led to innovative policies in irrigation techniques, wastewater processing, desalination, transportation, and policies focused on transnational sharing and coordination of water resources and distribution. In Israel, it has been a mission of the nation to make water policy a cornerstone of the nation's policy as well as its social, technological and economic development. In the southwestern United States, the policies and agreements that have grown around the Colorado River along with studies being performed by the U.S.

Department of the Interior in 2012 are clear indicators of the pivotal role that water will play in the future of that region. Governments are required to set policy to address the diminishing resource through conservation, management, and adaptation to find new sources. Governments will need to invest in infrastructure and find mechanisms for industry to be rewarded for investments in technologies like desalination.

## **Part 4 - Desalination Technologies**

Desalination is the technology on which we are focusing here. Sifting out minerals, boiling water for purity, and distillation of liquids are not new concepts. But the past century has seen great technological advances from the methods applied in the backwaters of the American frontiers to the emergence of mass volume industrial techniques. The prevailing methods for desalination are thermal processes such as multi-effect desalination and multi-stage flash desalination as opposed to filtration based methods such as reverse osmosis.

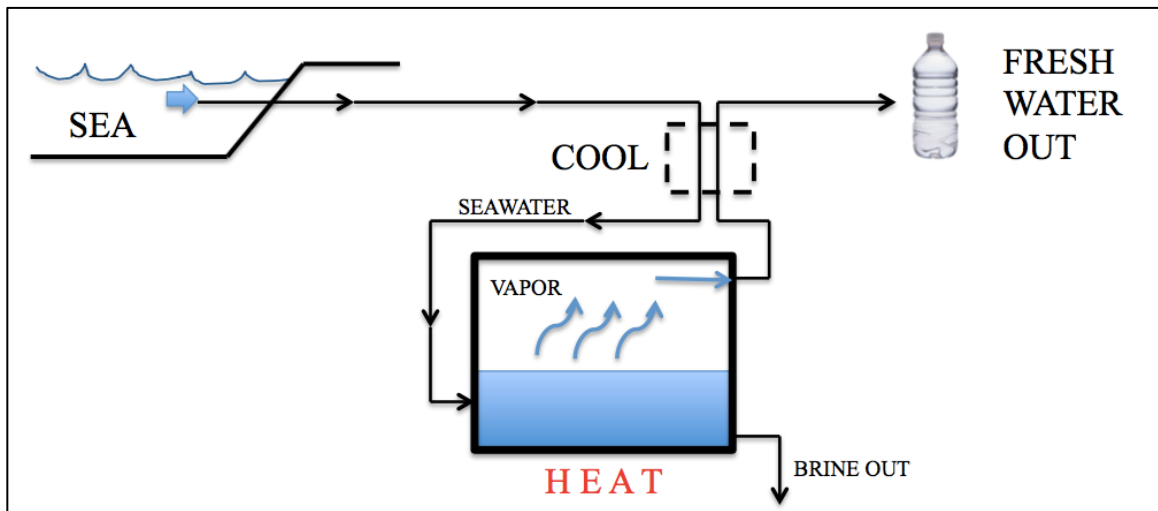
### **Sources of Salt Water (Brackish) Supply**

There are several sources of salt water. As noted in Part 1 of this study, seawater, which is the most commonly thought of source of salt water, has a total dissolved solid average of about 35,000mg/l. In addition, there are many ground water sources for salt water that will vary in levels of salinity that exceed 1,500 mg/l threshold. And, these sources are found in Texas, California, and Utah, as well as abroad in the Middle East, North Africa, and more. Clearly, seawater is a highly abundant source as it is 97 percent of the total water on the planet. There are a wide variety of salt- and mineral-rich water solutions, including seawater, which we will also refer to as brackish water.

### **Thermal Processes**

Thermal desalination uses basic distillation processes. In distillation, heat is introduced to bring the primary liquid in a solution to boiling point, separating it from the solutes. The

primary liquid is then condensed and collected. The distillation process is used in thermal desalination and involves evaporation of water and re-condensation of that water, where the saline and other mineral contents (brackish water) are left behind through the evaporation process—resulting in only fresh water being condensed and collected for use. A basic diagram of the principals of thermal distillation is shown in Figure 5.



**Figure 5 - Thermal Desalination: How It Works (Illustrated by G.S. Knoop, 2017)**

A common method employed in modern plants is multi-effect desalination (MED) shown in Figure 6, where an array of chambers with stepped reductions in pressurization facilitates recycling the captures or produces heat to repeat the distillation process several times. This method works on the principle that water boils at lower temperatures when air pressure is lower. Although this method is used throughout, most of the plants are burning fuel to produce heat to meet the required volumes. This process tends to be energy intensive and is based on late 19<sup>th</sup>-century distillation processes. For stand-alone plants, this method has gradually lost market share because of the extensive energy

required. As will be discussed later in this study in Part 5, the MED method has received renewed interest when developed in concert with thermal cogeneration technologies.

In MED design, the descending chambers allow the gradual use of heat energy, thus maximizing the amount of energy extracted. In each distillation process, referred to as an “effect,” heat is introduced into the brine, creating boiling points that are allowed to condense by cooled tubes (seawater) and are then collected. This distillation process is repeated in a connected array of similar chambers at lower pressure levels, with the used remaining heat from prior chambers. In the last chamber, the water vapor condenses in a heat exchanger, which is cooled by incoming seawater. The condensed water is collected from each chamber, and the remaining conserved heat is passed on progressively. A variety of heat sources are used to create the initial boiling effect, and several installations use a preheat cycle. These installations introduce a variety of opportunities for use of cogeneration heat energy. As shown in Figure 6, seawater is captured and introduced into a series of chambers with descending pressures. Steam heat is introduced to each chamber to create boiling point temperatures to separate the distillate from the brine. As energy is drawn from each descending chamber, the atmospheric pressure is reduced to allow for a lower boiling point temperature, facilitating thermal efficiency in maximizing the energy drawn from the source steam.

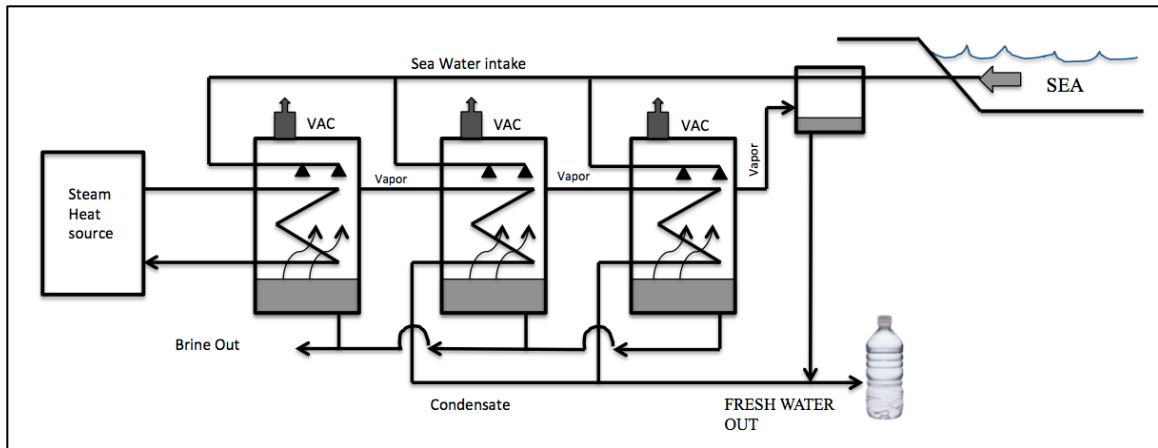


Figure 6 - MED Plant Diagram (Illustrated by G.S. Knoop, 2017)

There are multiple issues that should be weighed in MED plants. Like other heat processes, the quality of the brackish feed water is not as important as in the RO system technology, and this reduces the requirement for pretreatment filtrations. In comparing thermal technologies, the power consumption of MED is lower than that of the MSF plant, which opens additional options for cogeneration arrangements. MED arrays are designed to operate at lower temperatures. Lower temperatures reduce tube corrosion and the potential of scale formation around the tube surfaces. MED plants are considered to have the performance efficiency of multi-stage flash (MSF) plants. The MED process is considered more efficient than the MSF process with respect to thermal transfer and fresh water production cost.

MSF is the most commonly used thermal desalination process. In this method, seawater desalination process is distilled by flashing a portion of the water into steam in multiple stages in descending levels of pressurization where water is flashed by reaching the boiling point creating staged separation of water from the brackish brine.



MSF technology is considered the more efficient of the thermal methods. Water passes through tubes in each evaporation stage within the connected chamber where it is progressively heated. Final seawater heating occurs in the brine heater by the heat source. The heated brine flows through nozzles into the first stage, which is maintained at a pressure slightly lower than the saturation pressure of the incoming stream. As a result, a small fraction of the brine flashes to steam. The heat used to boil the water to flash comes from cooling from the brine flow, which lowers the brine temperature. Subsequently, the produced vapor passes through a mesh demister in the upper chamber of the evaporation stage where it condenses on the outside of the condensing brine tubes and is collected in a distillate tray. The heat transferred by the condensation warms the incoming seawater as it passes through counter-flow through the stage. The remaining brine passes successively through all the stages at progressively lower pressures, where the process is repeated. The hot distilled water also flows from stage to stage and cools itself by flashing a portion into steam, which is condensed again on the outside of the tube bundles. As shown in Figure 7, steam enters the brine heater along with the cold seawater (brackish water). The heated saline water is flashed into distillate in a succession of pressure-reduced chambers with brine falling to the bottom of each chamber where it can be drained out. The successive distillate is also collected and gathered. The remaining waste heat is ejected.

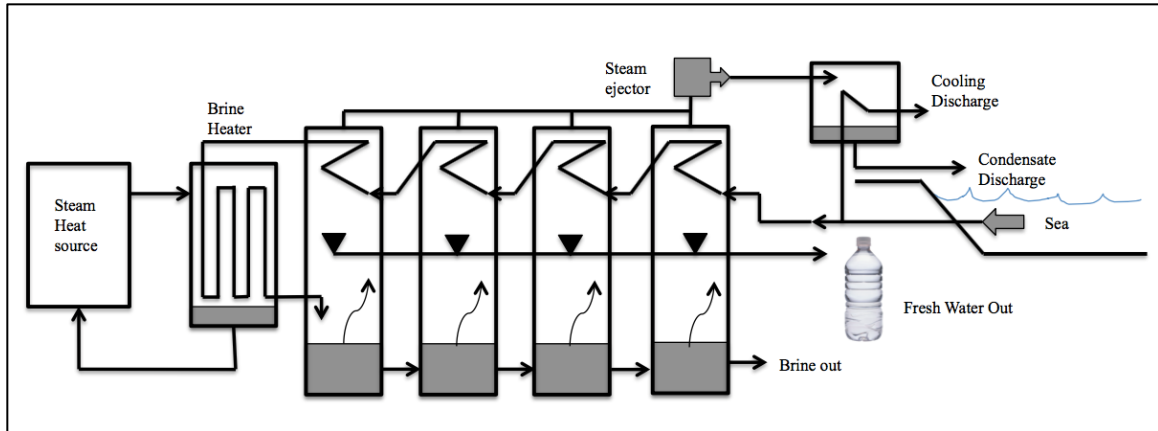


Figure 7 - MSF Plant Diagram (Illustrated by G.S. Knoop, 2017)

MSF plants are considered simple to operate and maintain with only a pump and a simplified set up of pipes and chambers. The quality of water effluent contains low dissolved solids because of the high level of purification that can be achieved. The quality of brackish feed water is not as important as it is in reverse osmosis, which requires extensive pre-treatment filtration. The MSF process is optimal when given a direct heat source. Therefore, operating plants at higher design temperatures improves their efficiency but causes scaling problems where salts such as calcium-sulfate precipitate on the tube surfaces and create thermal and mechanical problems, including tube clogging. Because of the heat required, MSF is an energy intensive process, which requires both thermal and mechanical energy, unless implemented in a cogeneration format. Adding more stages (chambers) improves the efficiency and increases water production, but it also increases the capital cost and operational complexity.

Then there is vapor-compression evaporation (MVC), a vapor compression distillation process used in combination with other thermal processes. In MVC, the heat for evaporating the brackish water comes from the compression of vapor. Like MED plants,

which use an array of descending pressure, MVC plants take advantage of the principle of reducing the boiling point temperature by reducing the pressure. The MVC process combines a mechanical compressor and steam jet to evaporate the brackish water. The process requires energy for the mechanical compressor and for the steam jet heat.

Seawater is sprayed on the outside of the heated tube bundle, creating flash evaporation. The first pump is used for depressurization and removal of the distilled water. A second pump is used to inject brackish water to facilitate evaporation while also pumping out brackish wasted water. The process creates distillation through the evaporative vapor being captured and pumped out as part of the depressurization.

MVC can operate with reduced energy and is generally found in smaller plants. This technology can also be found in concert with other processes like MED and MSF.

There are other methods, such as direct solar thermal, where solar photonic energy is captured and converted into heat. This heat can be used to bring brackish water to boiling point and create steam, allowing for the distilled vapor to be collected and fresh water produced.

### **Filtration Processes**

A different process is reverse osmosis (RO), which currently is the most prevalent in the marketplace today. RO separates the fresh water through the application of pressure on the saline water against a membrane, introducing pressure against the natural osmotic pressure. Rather than evening out in the water salinity solution (osmosis), the pressure

and the specialized membrane design produce the opposite effect to create separation. RO is often compared to dialysis.<sup>16</sup> This system can remove up to 99.5 percent of dissolved salts and all suspended matter from feed water sources including, municipal wastewater, brackish water, and seawater applications. Source water is pretreated to remove particulates. Then the water passes through a pressurization pump that increases the pressure to approximately 1000 lbs./in<sup>2</sup> whereupon it enters an array of RO modules where the fresh water is separated from the brackish salt water by filtration membranes. The waters are separated and distributed into fresh water and waste water piping arrays. They are set in arrays for large volumes of water to be managed and to permit operation and maintenance of removal of brackish material from the membrane and tank and for replacement of the membrane materials that reach saturation.<sup>17</sup> The RO method is now more commonly used because it can move large volumes of water using less electrical energy to control the pressure in the osmotic process. It does not require heat and so does not require transportation of heat engine fuels. In fact, some designs implement the use of energy recovery devices that are connected to the concentrated stream as it leaves the reverse osmosis pressure vessel.

---

<sup>16</sup> Nikolay Voutchkov, *Desalination Engineering: Planning and Design*, Page 11

<sup>17</sup> Nikolay Voutchkov, *Desalination Engineering: Planning and Design*, (New York: McGraw Hill 2013) Chapter 3

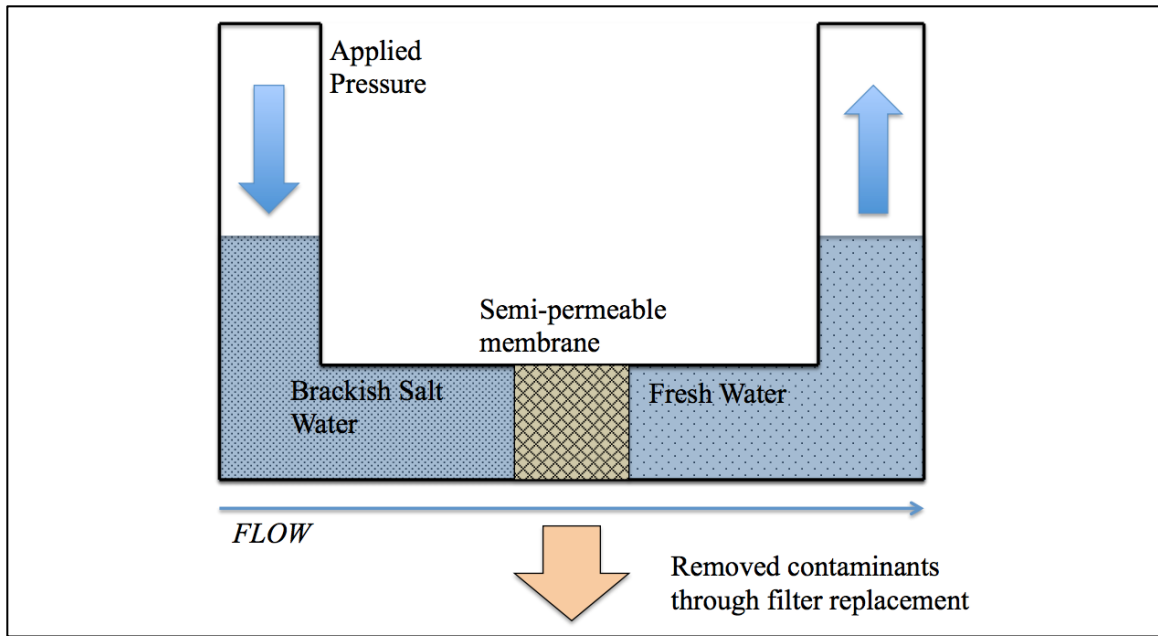


Figure 8 - Filtration Desalination Reverse Osmosis: How It Works (Illustrated by G.S. Knoop, 2017)

In the filtrations based desalination (Figure 8), there is a need to remove larger debris and particulates. This filtration is important because it protects the RO membrane surfaces from being clogged and also reduces the surcharging effects on the high-pressure pumps in the RO portion of the process. Pre-treatment and types of filters are designed around the feed water characteristics. In this stage, the brackish water is filtered to remove debris, particles, and suspended solids by an array of gravity filters.

RO systems are effective at creating consistent quantities of water with no heat process, but are dependent on energy for the pumping process (Figure 9). The material corrosion problems in the piping systems are significantly less compared to the thermal processes. However, there is energy and material required to supply and maintain the various filters in treatment and pre-treatment parts of the process. RO plants have benefited from the development of improved filters and membranes that are more resilient and affordable.

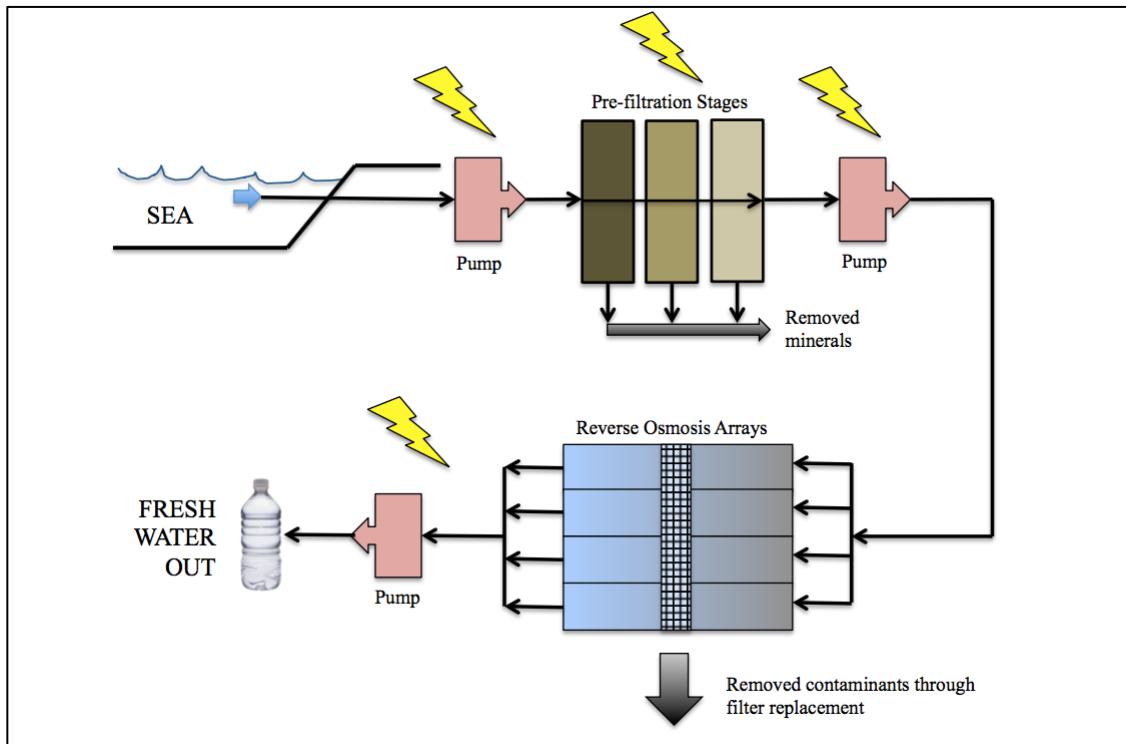


Figure 9 - Reverse Osmosis Plant Diagram (Illustrated by G.S. Knoop, 2017)

### Where and Why Different Systems Are Used

No doubt, there are advantages and uses for all the various desalination processes.

Traditionally we have seen the use of thermal desalination as a primary technology. As material and chemistry advanced, we have seen the introduction of filters capable of performing the high-quality filtration found in reverse osmosis. While these systems and the plants that use them require less energy than the thermal systems, they must have access to the electrical grid that enables the pumps and distribution systems to operate. Traditionally, thermal systems also require energy. As an example, some of the world's largest thermal plants operate in Abu Dhabi and consume hydrocarbon fossil fuels, which in turn create CO<sub>2</sub> and other emissions.

At one atmosphere, heating a gram of water takes about 4.18J/degree C, but the changes of stasis to become water vapor is about 2,257J In terms of energy; it is a cost of approximately 633kWh/M<sup>3</sup> to evaporate volumes of water. This is a heavy cost without changes in pressurization. Some of our engineered systems allow us to create this distillation process at a fraction of the energy. For example, MSF and MED plants may be closer to 25kWh/M<sup>3</sup> (85,000BTU/M<sup>3</sup>). Some thermal plants in the oil-rich Middle East use large quantities of energy to distill water.

We will find that different plants are going to introduce varying qualities of heat. Distillation plants measure thermal performance, not in terms of percentage, but as a ratio called the gained output ratio (GOR) or performance ratio (PR). The goal is to find the amount of water produced per unit of energy spent. Thus, you can have low performance of approximately 1:1 or good performance pushing in excess of 10:1. Use of waste heat energy is going to be in the lower range for these thermal plants. However, according to Tom Toner of Water Consultants International, the overall process for a cogeneration or hybrid plant can get into the range of 20 percent combined efficiency improvements.<sup>18</sup>

Worldwide, the variety of desalination processes result in reverse osmosis (RO) with 60 percent of the market being the dominant process—most likely driven by the lower capital costs for standard plants as well as the lower fuel/energy costs for this technology in stand-alone installations.

---

<sup>18</sup> John Toner, “Potential for thermal desalination in Texas”, Texas Water Development Board, Austin, 2004, page 4

## Cost of Water Desalination Methods

The cost of water in a stand-alone installation is lower for RO plants, which have 60 percent of the market over the thermal processes. The thermal processes of multistage flash (MSF) has approximately 26 percent of the market, and multi-effect desalination (MED) with/without vapor compression being around 8 percent of the market. These thermal processes have higher capital cost plants with fuel/energy costs when operated in a stand-alone installation. Other processes have approximately 6 percent of the market. To better understand how the costs interact with technologies and with the possible combinations of technologies, we borrow from the levelized cost of energy formula<sup>19</sup>:

$$\text{Levelized cost of energy (LCOE)} = \frac{((\text{Investment} \times \text{CRF}) + \text{O\&M} + \text{Fuel})}{\text{Annual Energy Output}}$$

$$\text{Note: Capital Recovery Factor} = \text{CRF} = (i(1 + i)^n) / (((1 + i)^n) - 1)$$

A sampling of the projected LCOE for heat engine technologies covered in this study would result in the following table (Table 1) based on 2022 projections being made by the US Energy Information Agency (EIA):

**Table 1 - EIA Table: “Estimated LCOE (simple average of regional values) for new generation resources, for plants entering service in 2022” (Figure limited to selected technologies) <sup>20</sup>**

Plant Type	Capacity Factor (%)	Levelized Capital Cost	Fixed O&M	Variable O&M (Including Fuel)	Transmission Investment	Total System LCOE	Total LCOE including Tax Credit
Coal with 30% Carbon Sequestration	85	94.9	9.3	34.6	1.2	140	140
Conventional Combined Cycle Gas Turbine	87	13.9	1.4	40.8	1.2	57.3	57.3
Advanced Nuclear	90	73.6	12.6	11.7	1.1	99.1	99.1
Biomass	83	44.7	15.2	41.2	1.3	102.4	102.4
Concentrated Solar Thermal	20	191.9	44	0	6.1	242	184.4

<sup>19</sup> NREL.com

<sup>20</sup> U.S. Energy Information Agency “Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2017, Table 1B



To convert the LCOE formula into the cost of manufactured industrial fresh water, the formula might look like the following for what we will call the levelized cost of water (LCOW):

$$\text{Levelized cost of water} = \frac{((\text{Investment} \times \text{CRF}) + \text{O\&M} + \text{Energy Cost})}{\text{Annual water Output}}$$

These types of calculations with the integration of efficiency factors for annual output can give us a way to see water production in a similar light that we use to judge our energy. To develop this further, Tables 2 and 3 extract figures from a study on the costs driving plant selections in the MENA countries, Almar Water Solutions developed comparisons in costs between thermal plants and filtrations plants, which was summarized here in Table 2:

**Table 2 - Almar Water Solutions O&M Costs in MENA Desalination plants <sup>21</sup>**

Project Type	Thermal Desalination	SWRO Desalination
<b>Variable O&amp;M Cost</b>	<b>62. 0-83. 0%</b>	<b>53. 5-68. 0%</b>
Energy Consumption	49. 5-55. 5%	37. 0-45. 0%
Chemicals, Membranes, Waste disposal	5. 0-7. 5%	16. 5-23. 0%
<b>Fixed O&amp;M Cost</b>	<b>17. 0-38. 0%</b>	<b>32. 0-46. 5%</b>
Environmental, Monitoring & Indirect Cost	5. 5-18%	7. 0-17. 0%
Labor & Maintenance	11. 5-20%	16. 5-23. 0%

In Table 3 when we look at the analysis of cost based on the type of plant and driven by the operations and maintenance (O&M) cost per square meter of water produced, we see that energy consumption is a significant cost driver for O&M in thermal plants. Overall the costs trend high due to a mixture in plant sizes.

---

<sup>21</sup> Almar Water Solutions, “Desalination Technologies and Economics: CAPEX, OPEX & Technological Game Changers to Come”, Page 15

**Table 3 - Almar Water Solutions Cost of Water per meter square in MENA Desalination plants<sup>22</sup>**

Desalination Plant Type	Capital Cost (Million US\$/MLD)		O&M Cost (US\$/ m3)		Cost of Water Production (US\$/ m3)	
	Range	Average	Range	Average	Range	Average
MSF	1. 7-3. 1	2.1	0. 22-0. 30	0. 26	1. 02-1. 74	1. 44
MED-TVC	1. 2-2. 3	1.4	0. 11-0. 25	0. 14	1. 12-1. 50	1. 39
SWRO Mediterranean	0. 8-2. 2	1.2	0. 25-0. 74	0. 35	0. 64-1. 62	0. 98
SWRO Arabian Gulf	1. 2-1. 8	1.5	0. 36-1. 01	0. 64	0. 96-1. 92	1. 35
SWRO Red Sea	1. 2-2. 3	1.5	0. 41-0. 96	0. 51	1. 14-1. 70	1. 38
Hybrid MSF/MED	1. 5-2. 2	1.8	0. 14-0. 25	0. 23	0. 95-1. 37	1. 15
Hybrid SWRO	1. 2-2. 4	1.3	0. 29-0. 44	0. 35	0. 85-1. 12	1. 03

This data was driving this company to favor use of reverse osmosis plants because of the clear cost advantage to these systems have in lower water costs. This aligns with most of the prevailing trends. But thermal plants can be more cost competitive when combined with another heat source through cogenerations/combined heat and power. This company's data allows us to deduce that there could be a significant change in the cost of water with the reduction of both the capital costs related to the boiler and steam plant capital costs as well as a change in the cost related to the O&M by a reduction in energy consumption.

In Table 3, we see low capital investment costs and lower energy costs in RO systems. However, these systems do have higher O&M costs related to the filtration and pre-filtration maintenance costs. Also noted is the fact that brackish waters with high mineral content require extensive pre-filtration prior to the RO process. In stand-alone plants, the thermal processes require energy to create steam. They are more capable of achieving desalination using more mineral intensive waters without the requirement of pre-

<sup>22</sup> Almar Water Solutions, "Desalination Technologies and Economics: CAPEX, OPEX & Technological Game Changers to Come", Page 17

treatment. Therefore, thermal processes will be higher in energy requirements but lower in operations and maintenance.

Why not just stop there? We don't want to burn fuels and create more CO<sub>2</sub>, so doesn't this mean that RO is the only way to go? There is an old saying, "One man's trash is another man's treasure," so let's look at this in the context of power plants. Heat engine plants, and especially power generation plants, use thermal processes that produce pollutants of many kinds. However, the one we are interested in is waste heat. By using the concept of combined heat and energy, or cogeneration, we can turn the formula around. If we could capture our heat from a source that is throwing it away, we could lower some of our capital investment as well as our cost of energy to run the thermal plant.

In simple terms, energy to produce desalination has a carbon impact. Reverse osmosis plants are considered the least energy intensive of the processes when using standalone configurations. In California, a review of 15 major RO seawater desalination plants that have been constructed since 2005 showed that "...On average, these plants use about 15,000 kWh per million gallons of water produced (kWh/MG), or 4.0 kWh per cubic meter (kWh/M<sup>3</sup>). We note that these estimates refer to the rated energy use, i.e., the energy required under a standard, fixed set of conditions. The actual energy use may be higher, as actual operating conditions are often not ideal. Membrane fouling, for example, can increase the amount of energy required to desalinate water."<sup>23</sup>

---

<sup>23</sup> Cooley and Heberger, "Key Issues for Seawater Desalination in California: Energy and Greenhouse Gas Emissions", page 5-6).

Many seawater plants use up to 6 kWh/M<sup>3</sup>. Thermal processes tend to use larger quantities of energy, with MSF using up to 28.5 kWh/M<sup>3</sup>, of which 23.5 kWh/M<sup>3</sup> (285mJ/M<sup>3</sup>) is in thermal energy consumption. MED plants use up to 22 kWh/M<sup>3</sup>, of which 19.5 kWh/M<sup>3</sup> (230mJ/M<sup>3</sup>) is in thermal energy consumption.<sup>24</sup> MED and MSF plants tend to produce more expensive water than RO plants in stand-alone configurations.<sup>25</sup> However when applying cogeneration configurations to reduce the cost of thermal energy production, there tends to be a shift, and the MED plants show the capacity to become the most affordable.

Let's take a look at our LCOW formula to see how costs might play into our perspective. For example, if we take two plants that produce 100,000M<sup>3</sup>/day of water, we will assume a maximum production of 36,500,000 M<sup>3</sup>/year, integrating efficiency factors. One example is reverse osmosis and one thermal MED:

**RO Plant LCOW**

*Investment = \$120,000,000*

*20 year CRF 5% = .08024*

*O&M= \$15,750*

*Energy = \$19,250*

*Annual Output = 36,500,000M<sup>3</sup>/year*

*Levelized cost of water =  $\frac{((\$120,000,000 \times .08024) + \$15,750 + \$19,250)}{36,500,000}$*

*LCOW= \$0.27/M<sup>3</sup>*

---

<sup>24</sup> Al-Karaghoulin and Kazmerski "Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes", Page 347

<sup>25</sup> Al-Karaghoulin and Kazmerski "Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes", page 349

**MED Plant LCOW**

*Investment = \$140,000,000*

*20 year CRF 5% = .08024*

*O&M= \$6,300*

*Energy = \$7,700*

*Annual Output = 36,500,000M<sup>3</sup>/year*

$$\text{Levelized cost of water} = \frac{((\$140,000,000 \times .08024) + \$6,300 + \$7,700)}{36,500,000}$$

$$\text{LCOW} = \$0.31/\text{M}^3$$

These costs are going to vary across marketplaces and will be different from outcomes of the MENA costs, because these are the cost at the plant and the MENA cost will include the full cost of infrastructure, which includes the water and sewer distribution networks. In addition there will be a variety of cost affected by larger and smaller plants with higher and lower efficiencies. The plants modeled are both primary production plants over 100,000 M<sup>3</sup>/day; generally considered larger plants. What we can see is that while the RO plant is more expensive on O&M, it is less expensive in capital costs. This is the common way that we have seen RO plants becoming more prevalent. If we tested whether a MED thermal plant could cost less if we paired it in a cogeneration configuration, we could assume that the removal of the steam boiler and integration into a combined heat and power system would reduce plant cost by 10 percent and eliminate the energy cost. This would give us a calculation as follows:

**MED Plant LCOW with cogeneration**

*Investment = \$126,000,000*

*O&M= \$6,300*

*Energy = \$0*

$$\text{Levelized cost of water} = \frac{((\$126,000,000 \times .08024) + \$6,300 + \$0)}{36,500,000}$$

$$\text{LCOW} = \$0.28/\text{M}^3$$

The cost of multi-effect desalination thermal plant LCOW can come within reach of the reverse osmosis desalination plant in a cogeneration configuration.

Part 5 will look at what those types of thermal parings might look like. The calculation shown above only takes into account the reductions of costs on the MED plant in cogeneration; this would apply to installations that are retrofitted to existing power plants. New power plants that integrate cogeneration concepts from the start may find additional capital cost savings due to the paring, which may also reduce the LCOE.

## **Part 5 – Cogeneration Opportunities for Power Generation and Industrial Process**

### **Cogeneration: Waste Energy to Usable Energy**

This cogeneration concept is where reducing carbon dedicated to desalination (increasing the thermal efficiency of power plant fuel consumption through combined use) creates opportunity to retrofit existing plants for improving beneficial output, thus reducing the negative impacts of plant waste heat on riparian ecosystems.

To create our cogeneration process (using of waste heat to facilitate the thermal distillation processes), we need to look at the prime candidates for capturing this energy.

The first of these candidates are heat engines and power plants. The heart of power generation using heat engines is geared toward steam turbines that create the conversion from heat energy to mechanical energy to electrical energy. The steam turbine is a heat engine that follows the Rankin cycle, in which heat is transmitted to a working fluid in an evaporator to vaporize the fluid into steam. The high temperature steam is then fed through a turbine, where it imparts its energy to the rotor blades, causing the rotor to turn from the expansion of the steam as its pressure and temperature are reduced (passage of energy from steam pressure to mechanical rotation). Often, there are secondary loops that take the steam and introduce it to a secondary turbine blade array to add to the rotational forces. The reduced heat steam leaving the turbine is then condensed and pumped back in liquid form as feed for the evaporator. Excess waste heat is ejected.

Where does the heat come from that creates these steam temperatures exceeding 900 degrees Celsius? Some of the most common systems, such as coal plants, biofuel plants, waste energy plants, and other incendiary processes, involve the burning of hydrocarbon fuels to create heat. In addition, hydrocarbon processes capturing rejected heat from gas-turbines can also run steam turbines. Nuclear power and concentrated solar thermal are two carbon-free processes that also run turbines. All these systems reject heat into rivers, cooling towers, and other cooling mediums. The rejected heat contributes to the thermal efficiency of these plants, which is seen in numbers ranging from 25 to 60 percent, depending on the fuel and design of the plant. This process leaves a great deal of unaccounted and unused energy.

Cogeneration (also termed combined heat and power) is a design configuration where waste heat ejected from power generation (the unused part of the thermal efficiency) can be used in other processes. Examples include the exchange of this heat to create domestic heating steam or heating for hot water. For this study, the interest is in capturing this heat to apply to low-pressure thermal desalination such as MED and MSF processes. The following paragraphs and diagrams will explore different kinds of heat engines that have waste heat available for this type of cogeneration.

The U.S. Energy Information Administration (EIA) provides us with formulas for heat rates as a measure of the efficiency that is applied to the performance of electrical power generation in heat engine plants as it that converts a fuel into heat and into electricity. The heat rate is the amount of energy used by an electrical generator or power plant to



generate one kilowatt hour (kWh) of electricity. EIA expresses heat rates in British thermal units (Btu) per net kWh generated. Thus, they calculate net generation as the “...amount of electricity a power plant (or generator) supplies to the power transmission line connected to the power plant. Net generation accounts for all the electricity that the power plant consumes to operate the generator(s) and other equipment, such as fuel feeding systems, boiler water pumps, cooling equipment, and pollution control devices.”<sup>26</sup>

Thus, the formula for efficiency for in thermal plants can be as follows:

$$\text{Heat rate (BTU/kWh)} = \text{energy input (BTU/hr)} / \text{power output (kW)}$$

And:

$$\text{Energy/heat rate} = \text{efficiency}$$

## **Industrial and Power Generation Technologies**

Each type of plant technology will create a similar formula to create the expected efficiency of the plant. Let us look at some of these:

### **Coal Plants**

Coal plants are designed to convert energy from the burning of coal into mechanical energy that spins an electrical generator's steam turbine. The combustion of coal from the firebox is passed via radiation to an array of pipes in the boiler that are looped and

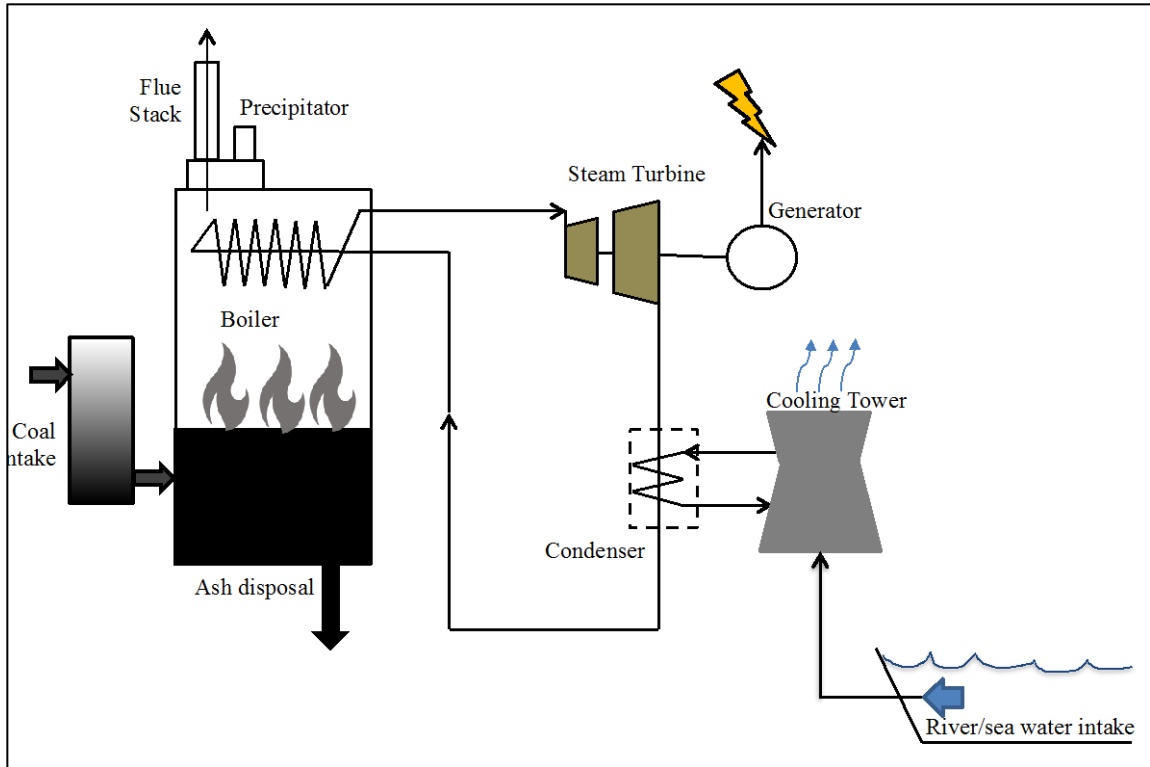
---

<sup>26</sup> EIA.org

convey water being converted to steam. The steam is then used to spin the turbines. In both the combustion and steam cycles, there is waste heat affected into a cooler medium (rivers, oceans, and air). Because large quantities of heat are rejected, we see a thermal efficiency of around 33 percent for most coal plants. This efficiency makes coal plants prime candidates for sharing the thermal energy (in other words, cogeneration).

Cogeneration is most commonly used in coal plants that are adjacent to or serving campuses where the waste heat can be converted to steam heat for domestic heating uses. This can also be applied to thermal desalination processes.

An example of a typical coal plant layout is in Figure 10. Heat is ejected in both the flue stack and in the condenser to the cooling tower. The lower thermal efficiency gives us clues where we can find high cogeneration opportunity. Typically, a heat recovery system would be tied into the flue stack. Then the cogeneration system would take the place of the cooling tower, but perform similar duty. The heat energy would be captured in a heat exchanger and then conveyed in the form of low pressure steam in a piping infrastructure to be used for heating homes, heating domestic water, or other uses. In this study, the interest is using this heat energy for thermal desalination.



**Figure 10 - Coal Fired Power Plant Diagram (Illustrated by G.S. Knoop, 2017)**

To adapt existing plants for cogeneration configurations and using waste heat energy for thermal desalination we need to follow the heat ejection locations. In this case, the opportunity is to capture heat from thermal exhaust at the boiler and thermal rejected heat at the steam turbine. Heat exchangers can be introduced to capture the exhausting heat in the flue stack. This heat will be sub-boiling temperatures, which is why the use of an MED pairing would be optimal. To perform optimally, MED plants do not require the high temperatures that MSF plants do. The captured heat energy can be introduced as the input heat source in a MED plant configuration. As stated before, the heat capture will be only at a sub-boiling temperature. Otherwise, plant engineers would be integrating the additional captured heat to run the steam turbines. MED chamber arrays can be designed to take the heat that is sub-boiling for one atmosphere and use it to create the endothermic

reactions that would facilitate distillation at lower atmospheric pressures in each chamber. Similar arrangements can also be made for MSF arrays, but they would not be operating at optimal design efficiency without the introduction of supplementary high-temperature heat sources.

The concept is to increase the thermal efficiency by introducing other uses for the waste heat energy. Many stand-alone thermal desalination plants require the hydrocarbon fuels to be burned to create the heat source, making these processes carbon intensive. By using cogeneration heat sources, the carbon footprint of the distillation process is much lower or could be counted as zero. In addition, the power plants that use river, lake, or seawater for cooling may be introducing heat that negatively impacts the local ecosystems.

### **Oil Fired Plants**

Oil fired plants are less common in the US, but diagrammatically are similar to coal fired plants. Much like coal plants, oil fired plants have a thermal efficiency in the range of 33 percent, and most are found in the East Coast regions of the U.S. Oil fired plants eject their heat similarly from the waste heat in the boiler and from waste heat at the steam turbine.

As in coal fired plants, waste heat energy can be captured in heat exchangers in both the boiler exhaust and in the cooling tower processes where the plant is ejecting heat. This can be tied into a cogeneration arrangement to facilitate the MED or MSF processes.

Here again is the opportunity to capture zero added carbon to accomplish thermal desalination and raise the thermal efficiency of the plant.

### **Waste-to-Energy Plants**

Waste-to-energy plants allow municipalities to tackle the growing challenges of dealing with municipal solid waste by using the incineration process as a method to burn the waste and convert it to fuel for power plants. These plants tend to burn at lower temperatures and have lower thermal efficiencies than fossil fuel plants, but generally are diagramed in the same way. They are ejecting heat from the boiler and the steam cycle.

Again, waste heat energy can be captured in heat exchangers in both the boiler exhaust and in the cooling tower processes where the plant is ejecting heat. This energy can be tied into a cogeneration arrangement to facilitate the MED or MSF processes.

Often, waste-to-energy plants receive criticism for their negative environmental effects resulting from pollutants exhausted from the incinerator. However, by creating a source for fresh water at zero added carbon and an improved overall thermal efficiency of the plant, we can offset the negatives of the waste-to-energy exhaust.

### **Combined Cycle Gas Turbines**

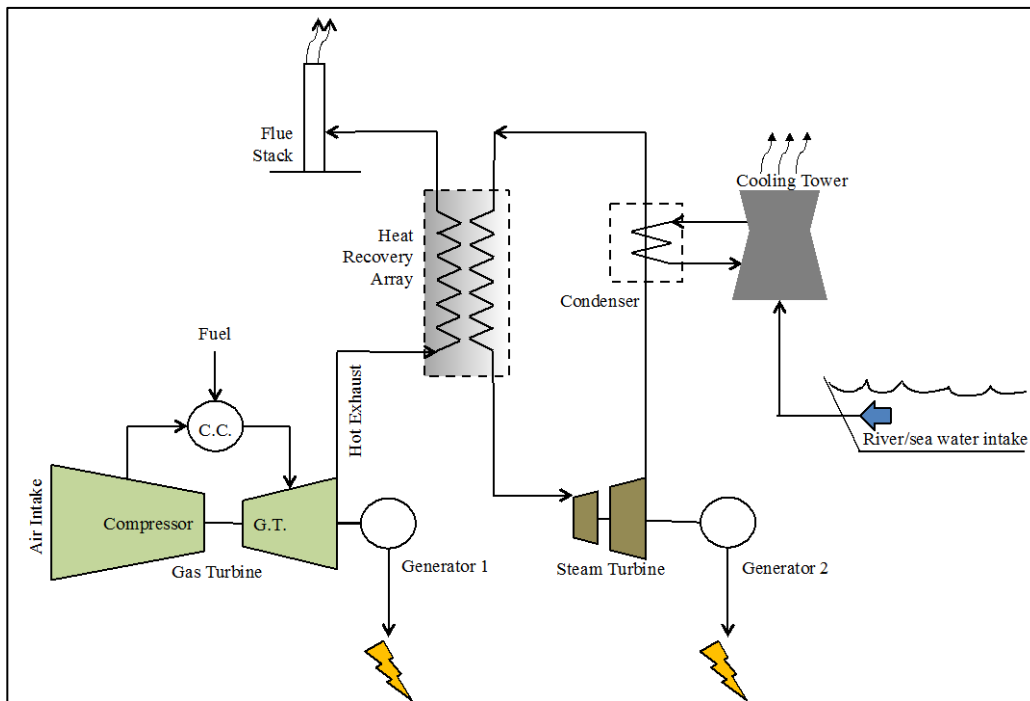
Gas turbine plants were once thermally inefficient, ranging around 25 percent thermal efficiency and producing large quantities of atmospheric waste heat energy. These plants were designed to use heat and pressurization into a gas turbine jet engine to create the

spinning mechanical energy that can be converted in a generator into electricity. The exhaust heat was ejected into the atmosphere. The combined cycle is a cogeneration concept. The ejected heat is directed into an array of piping carrying water that is converted to high-pressure steam. This steam is used to power an additional generator. Greater quantities of heat are captured in this type of plant, leading to thermal efficiencies in the range of 50 to 60 percent. Figure 11 diagrams a typical CCGT plant. The whole design of the plant is using cogeneration concepts to capture heat, enough to run a steam turbine; and there is still waste heat energy being ejected into cooling towers.

For gas turbine plants, there are different solutions for cogeneration integration of desalination plants. The most basic is to capture waste heat from the thermal ejection at the cooling tower. This may lead to a very low production MED plant. To create a pairing with a larger MED or MSF plant, then some of the heat in the second cycle (steam cycle) would have to be divided to create higher temperature steam and higher volumes of energy that could be used run larger desalination plants.

Simple gas turbine plants may have low thermal efficiencies for power generation alone at 25 percent. However, there is great potential for capturing the waste heat energy from the thermal gas turbine exhaust and converting it into heat for MED processes. General Electric has recently outlined this approach in a patented process described in U.S. Patent 8545681 B2 "...supplying exhaust gases from a gas turbine set used to generate electrical power to a heat recovery steam generator (HRSG) and then directing the steam from the HRSG to a steam turbine set. Salinous water is supplied into an effect of the desalination

unit. Steam exhausted from the steam turbine set is utilized in the effect of the desalination unit to produce a distillate vapor and brine from the effect by heat exchange. Additionally, steam is introduced steam from at least one additional heat source from the combined-cycle power generation plant to the effect to increase the mass flow rate of steam into the effect....”<sup>27</sup>



**Figure 11 - Combined Cycle Gas Turbine Power Plant Diagram (Illustrated by GS Knoop 2017)**

The patented process above alludes to arrangements for combined cycle units. In a combined cycle turbine unit, tapping into the ejected heat from the steam turbine process can capture waste heat. At sub-boiling temperatures, this ejected heat can be harvested to run MED at designed levels of depressurization.

<sup>27</sup> General Electric, “U.S. Patent 8545681 B2”

## Nuclear Energy Plants

Nuclear plants have been looked at for cogeneration fueled by technologies that have been created by the US Navy for nuclear powered vessels. Nuclear plants have received a great deal of attention as potential candidates for cogeneration for desalination. The waste heat energy can be captured to integrate with MED and other thermal processes. Nuclear plants for cogeneration can be even more effective in reducing carbon emissions. A typical plant layout is shown in Figure 12. As described with other examples, the cogeneration heat sharing can occur at the cooling tower location and additional heat capture can be drawn from the primary steam loop. There may need to be redundancies for cooling tower as a failsafe measure given the safety issues with nuclear plants.

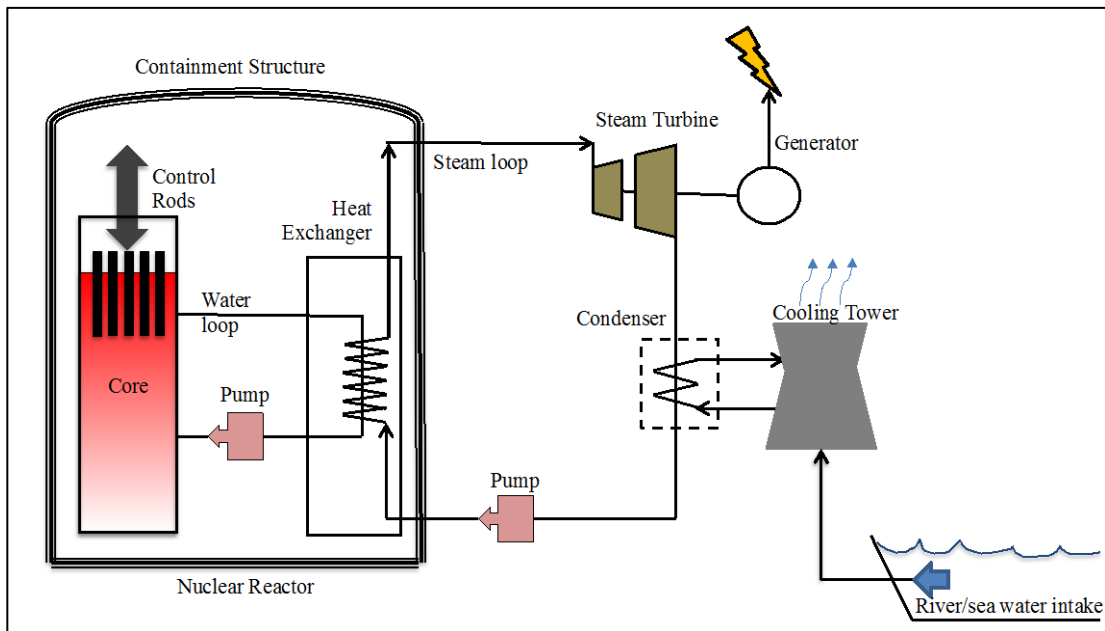


Figure 12 - Nuclear Power Plant Diagram (Illustrated by G.S. Knoop, 2017)

The World Nuclear Association reported that, “Small and medium sized nuclear reactors are suitable for desalination, often with cogeneration of electricity using low-pressure



steam from the turbine and hot seawater feed from the cooling system. The main opportunities for nuclear plants have been identified as the 80-100,000 m<sup>3</sup>/day and 200-500,000 M<sup>3</sup>/day ranges. U.S. Navy nuclear powered aircraft carriers reportedly desalinate 1500 M<sup>3</sup>/day each for use onboard.”<sup>28</sup>

This is not a new technological application. The Soviet Union, and later Kazakhstan, managed a nuclear plant in Aktau that, starting in 1972, was producing 80,000 M<sup>3</sup>/day for more than 27 years.

The World Nuclear Association further reported that multiple plants in areas such as Russia, Eastern Europe, and Asia as developing desalination cogeneration with nuclear plants. “South Korea has developed a small nuclear reactor design for cogeneration of electricity and potable water. The 330 MWt SMART reactor (an integral PWR) has a long design life and needs refueling only every 3 years. The main concept has the SMART reactor coupled to four MED units, each with thermal-vapor compressor (MED-TVC) and producing total 40,000 M<sup>3</sup>/day, with 90 mWe.”<sup>29</sup>

### **Concentrated Solar Thermal Power Generation (CSP)**

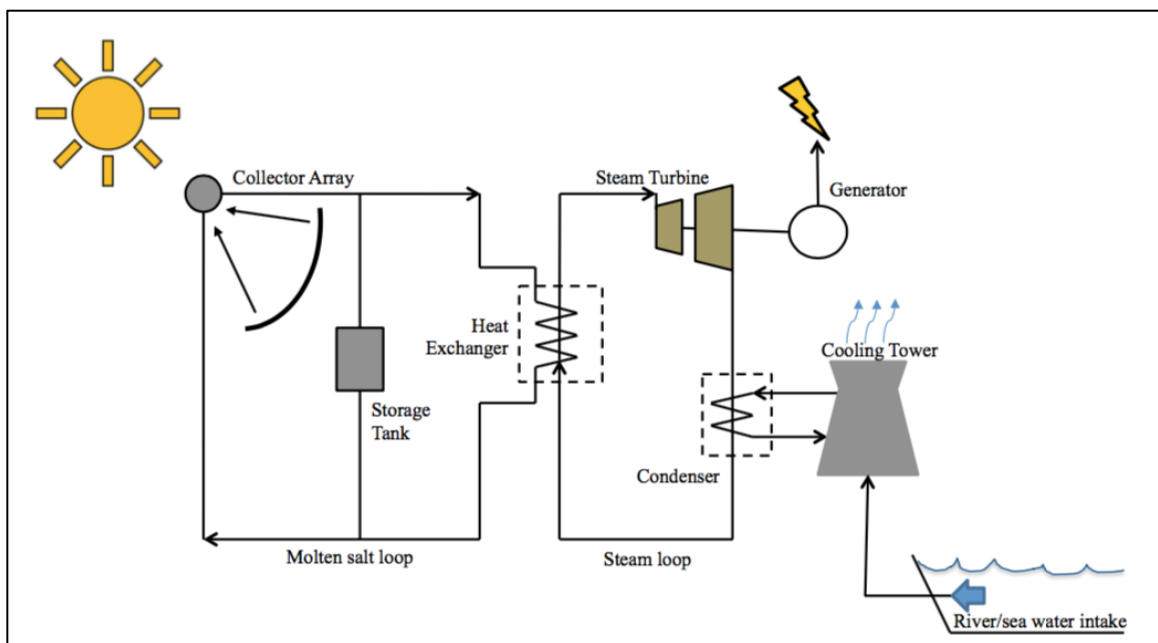
A re-emerging technology is the concentrated solar thermal plant. Not commonly known is that harvesting solar energy for industrial energy applications dates back to a steam engine that was powered by a solar reflector invented by Augustin Mouchot and

---

<sup>28</sup> World Nuclear Association “Desalination”, Non-Nuclear Applications World Nuclear Association, <http://www.world-nuclear.org>

<sup>29</sup> World Nuclear Association “Desalination”, Non-Nuclear Applications World Nuclear Association, <http://www.world-nuclear.org>

exhibited at the World's Fair in Paris in 1878 (based on research he had performed since 1871). The use of solar energy to heat water and create steam would be further developed by Frank Shuman in the early 20<sup>th</sup> century. However, this revolutionary concept would take the remainder of the century to gather steam. In the age of digital controls, light sensors, advanced chemistry, and advanced glass technologies, the concentrated solar thermal plant has come of age. Figure 13 shows a diagram of a typical plant.



**Figure 13 - Concentrated Solar Thermal Power Plant Diagram (Illustrated by GS Knoop 2017)**

There are multiple CSP power generation plant configurations from arrays of parabolic troughs to arrays of focal dishes—in both cases with the absorber and heliostat reflectors packaged together. Larger scale plants have been developed where a tower structure with the receiver is set at a central location to allow dozens to hundreds of heliostats (often with mechanically enhanced solar tracking) to direct, focus, and concentrate the reflected solar light waves to a single collection point at the receiver. Within the receiver, the concentrated

solar flux is absorbed through ceramic-like tiles, and the resulting super-hot air transfers the heat to pipes of molten salts. The heated molten salts are circulated to storage and a heat exchanger where the heat is converted to steam, which runs the steam turbine generator. There is a cold side recirculation system that loops the process.

The molten salts retain their heat, which allows for the plant to continue generating energy through the residual stored heat during the less optimal collection conditions. The high absorption and high heat capacity of the molten salts is key to creating a safe, circulating medium with a high heat capture rate it can retain as it transfers the heat to storage and heat exchange process.

As with the other heat engine configurations, the steam turbine is operated by steam generated in the heat exchanger. These plants also have waste heat energy that is usually expelled through a set of cooling towers.

This elegant use of solar energy still provides us with a source of thermal energy that can be used to boil water at lower pressures, permitting us to use MED and MSF technologies in a cogeneration configuration to create fresh water. This is achieved by introducing a loop of all-waste heat ejection (mostly after the steam turbine cycle) into the desalination array as the primary heat source. By design, this would be sub-boiling water that is being released in cooling towers, which is why the MED set-up will be for lower atmospheric pressures.

## **Industrial Plants**

Industrial processes in oil refineries, metal refineries, and other heat-intensive processes require high heat levels as catalysts for chemical processes.

### **Oil Refineries**

Oil refineries are a potential source for waste heat harvesting for cogeneration-like processes. Many of the refineries in the U.S. are adjacent to coastal areas to take advantage of proximity to international shipping to import foreign crude oil and ship domestic and foreign oil that has been refined into a variety of petrochemicals. Well refineries can employ waste heat recovery, which allows them to capture heat exhausted from the various combustive processes to be captured and reused.

A study by Mauro Capocelly addressed the use of waste heat recovery in oil refineries and tied together both industrial and academic studies that trace the feasibility of using rejected heat (even after recapture through heat recovery) to be used for multiple effect distillation and multi stage flash desalination, because the low temperatures below 200° C.<sup>30</sup>

### **Bessemer Steel Production and Other Heat Intensive Industrial Processes**

Industrial steel manufacturing is a heat intensive process. A great deal of attention has been given to the capture and reuse of this waste heat energy for power generations using Kalina cycle generators and other medium heat energy generation. This heat becomes ideal for capture in multi-effect distillation and multi-stage flash desalination.

---

<sup>30</sup> Mauro Capocelly, "Waste Heat Recovery in the Oil & Gas Sector", page 3

## **Pulling It Together**

There are existing sources for capturing waste heat from power generation and industrial waste heat that give us access to energy for desalination from ejected waste heat. With over 66 quadrillion BTUs of energy wasted every year in the US, there is clearly opportunity to capture even a part of this energy in a combined heat and power configuration with MED desalination to create a significant supply of industrial fresh water. Figure 14 illustrates the concept for combining a thermal plant (MED or MSF) with typical heat engine plants. For example, a concentrated solar thermal plant in combination with a combined cycle gas turbine plant can create a baseline power generation plant that has reasonably high efficiency. The plant still ejects large quantities of low level steam heat that can be shared in a cogeneration configuration to contribute to MED desalination processes that have coordinated pressurization levels to make best use of the available heat ejected. Figure 14 also shows the locations where that heat energy can be captured and tied to a desalination plant. Not shown is the possibility that additional supplementary heat can be drawn from the steam loop to increase the productivity of the desalination, but this comes at a cost to the efficiency of the power plant.

Klaas Visser is an engineer in Pennsylvania that studied the beneficial use of this waste heat energy to both the delineation process and in creating better use of the energy consumed in a power plant. He concluded that: “Using heat pumps to condense steam in Steam Power Plants (SPPs) allows the recovery of waste heat at high efficiency. The

amount of heat becoming available as useful heat at the discharge of the heat pump amounts to 150 percent to 200 percent of SPP electrical energy production. Heat rates vary from 8,500 to 10,800 BTUs/kWh. This heat may be used for different purposes like MED desalination and district heating. This basically means that up to 90 percent or more of the energy in the fuel consumed by the SPP is becoming available as usable energy. This represents great value for money when considering that SPPs normally dispose of their condensation heat directly into the environment via cooling water from cooling towers, rivers, lakes or the sea.”<sup>31</sup> We saw reductions in the LCOW for desalination plants using cogeneration configurations. Mr. Visser also introduces the potentials in reductions to the LCOE.

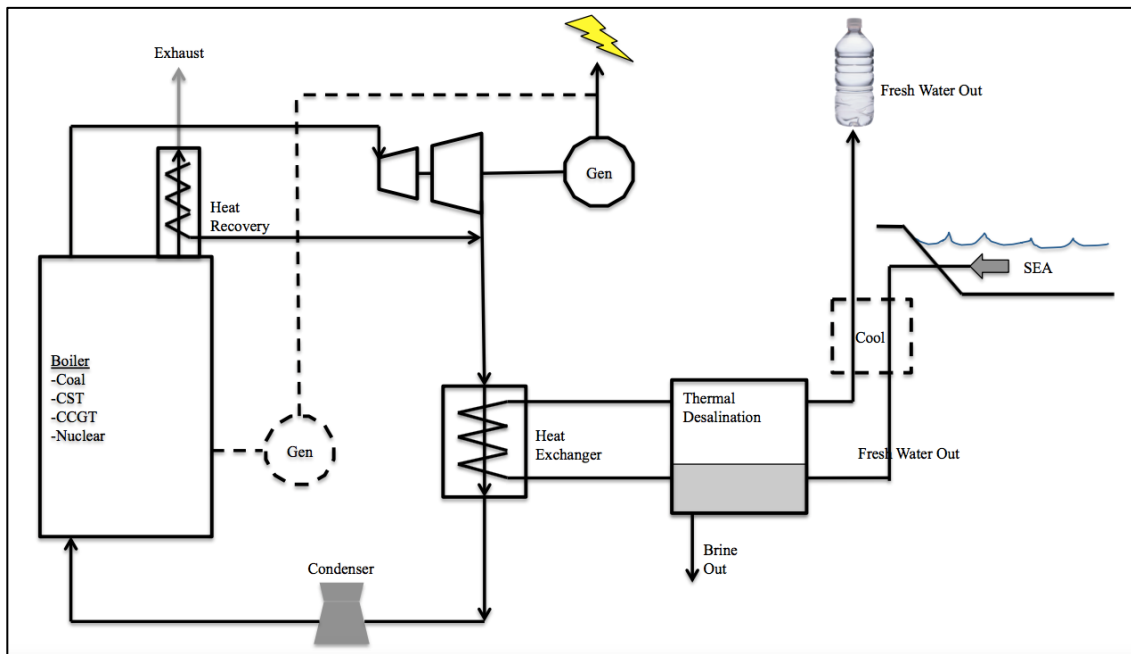


Figure 14 - Cogeneration Power Plants and Thermal Desalination (Illustration by G.S. Knoop, 2017)

<sup>31</sup> Klaas Visser, “Waste Heat Recovery for Desalination from Steam Power Plants”, *Water Online*, 2014

## **Part 6 – Policy**

### **Current Policy Structures**

Policies are required to place social and market controls over access to fresh water, movement of the resource, conservation of natural sources, protection of the resource from damage, and management of the marketplace. The price of water may not have all the costs incorporated. They are likely not to recognize the negative externalities of aquifer depletion built into the price of water. Lacking are policies that facilitate the increasing of water supplies through industrial processes. Nor is there strategic framework to move larger quantities of water from those processes to water users.

In California state programs, policies and agency requirements must be considered when developing a desalination plant. “These include environmental review requirements under the California Environmental Quality Act, the issuance of permits by the Coastal Commission, the Integrated Regional Water Management Planning process, and policies of other state agencies, such as the State Lands Commission and the State Water Resources Control Board. These agencies have increasingly emphasized the importance of planning for climate change and reducing greenhouse gas emissions. While none of these preclude the construction of new desalination plants, the State’s mandate to reduce emissions creates an additional planning element that must be addressed.”<sup>32</sup> California is also a leading-edge state in the development of energy efficiency and carbon reductions for industrial power, which could eventually be translated to industrial desalination.

---

<sup>32</sup> Cooley and Heberger, “Key Issues for Seawater Desalination in California: Energy and Greenhouse Gas Emissions”, Page 2.

Policies have tended to be more protective in nature. This paper aims to further help shape policies into productive frameworks for protection of our natural resources, restoration of our water supply, protection of the environment, creation of master-planning frameworks for distribution, and transformation of relevant technologies.

### **Infrastructure**

One of the greatest challenges for industrial levels of desalination is the transportation of source water to the plants. In the U.S., for example, much of the properties along the coastal regions will require significant work in land rights, property, right of way, or environmental protection to create access to the vast ocean waters. In addition, as we take in lessons learned from the industrial damages from recent super storms including Katrina, Sandy, Harvey, and Maria, we have a preview of the possibilities of coastal flooding as ocean volumes grow from rising global temperatures.

Is waste heat a pollutant? The dictionary states that pollution is “...the presence in or introduction into the environment of a substance or thing that has harmful or poisonous effects.” While heat is not poisonous, it may be that waste heat introduces the potential of environmentally altering temperatures—which should be considered a pollutant. If policies can be adopted that classify waste heat as a pollutant that requires controls, then there is an opportunity to leverage that control to drive innovation. If power plants and industrial plants had to control their heat ejection, then they would look for productive and potentially profitable ways to reuse this energy such as cogeneration.



## **Policy Framework**

Policy frameworks involve a multipronged approach. Policies that will work effectively to overcome water stress and encourage innovation and partnership between industry and government must touch on a variety of issues and present a variety of response vectors for industry.

California is a key state in the most water stressed parts of the U.S. and is the testing ground for many sustainable policies in the country. The State Water Resources Control Board (State Water Board) adopted an amendment to the Water Quality Control Plan for the Ocean Waters of California (Ocean Plan) on May 6, 2015. To date, little existed for addressing permissive access to ocean waters while protecting marine ecosystems from the effects of the industrial mining of seawater.

The Desalination Amendment was written to provide the structure for access to drawing out seawater for desalination facilities along the California coastline. Several issues are involved, the first being the drawing of seawater for use by desalination plants without creating adverse dangers to wildlife and beach tourism. In addition, there was need to clarify the effects of and rules for the dumping of brine water back into the ocean. There are concerns that the discharge with a change in salinity and mineral concentration might create harmful effects on the discharge areas. The Desalination Amendment works to clarify the permissions, access, and oversight to facilitate the growth of this needed industrial utility. On January 28, 2016, the Amendment was approved into law. The EPA

followed by approving the portions of the Desalination Amendment that implement the federal Clean Water Act on April 7, 2016. California led the way and the act is now in full effect.<sup>33</sup>

This policy is very important for establishing both methods and creating a discourse on infrastructure for seawater to freshwater distribution. In addition, the law works to stay ahead of the protection of marine species. The amendment addresses technologies and best practices while placing responsibility on plant developers to design and implement mitigation measures for environmental protection. This perhaps shows that the desalination industry will benefit from some of the struggles (for example, harming avian life and bats) encountered by wind farms and concentrated solar thermal plants. At the time of the act, 5 out of 11 of California's desalination plants were in marine protected areas (MPA), national marine sanctuaries (NMS), or areas of special biological significance (ASBS). The Claude "Bud" Lewis Carlsbad Desalination Plant, opened at the end of 2016, adding the nation's largest plant into the California fleet and raising the importance of smart legislation and guidance around an industrial utility that will continue to grow in throughout the U.S. As we saw earlier in Part-3, desalination in the Colorado River basin is expected to grow significantly by 2060 in order to meet the growing demands in the region.

### **Licensing Facilities Dependent on Thermal Efficiency**

Current policy structures do not create any legal framework that is punitive. However, license to operate heat engine power plants could be written to require levels of efficiency

---

<sup>33</sup> California Water Desalination Amendment 2016

for certain types of plants—especially those that have high capacity factors and are operating to handle base load. Creating fines or preventing operational licensing restrictions for these types of plants would help push the power industry toward more efficient, lower carbon fuel mixes. This focus on operational efficiency would create an additional push toward combined heat and power configurations as suitable means for enhancing the overall useful efficiency of the plants.

### **Tax Incentives for Encouraging Industrially Produced Potable Water**

The law could also be shaped to create equivalency points on renewable energy credits (REC) offset by CHP MED/MFS desalination systems. Similar incentives could be built around renewable energy powered RO. The production of water being essential to offsetting the large increases in demand, while also being essential to the resiliency of needed systems, make tax incentives built around industrial fresh water production ideal for fostering positive change driven by economic forces.

### **Tax Incentives for Capital Investment in Cogeneration for Power Plants to Raise Total Thermal Efficiency**

One of the structures that rose out of the 2008 recession was the American Recovery and Reinvestment Act (ARRA) of 2009. Part of this act included a tax incentive around investment in cogeneration (combined heat and power) technologies. The CHP investment tax credit was a 10 percent credit for the first 15MW of real property and was active from October 3, 2009 to January 1, 2017. Qualifying systems must have 60 percent efficiency and produce a minimum of 20 percent of their useful energy in electricity and

a minimum of 20 percent of their useful energy in thermal processes; a perfect fit for cogeneration for thermal desalination. This law has now expired, but should be revisited and extended.<sup>34</sup>

We should look at creating an incentive that would roll a tax credit into the cost of energy as we saw in the adjusted cost of energy for the concentrated solar thermal plant where the LCOE would not be enough to make it cost competitive due to the capital investment costs. In this case, adding a cogeneration MED plant pairing could earn tax credits that would adjust the cost of energy. Another opportunity would be to apply the cost into the water production cost. We now return to our earlier formula and calculation from Parts 4 and 5 where we looked at the comparison of costs between a RO plant and a MED plant; then added the cogeneration scenario to the MED plant. If we applied a \$0.05/M<sup>3</sup> adjustment from a tax credit, we would see the results change further to show that the MED plant can have a lower LCOW than the RO plant as follows:

**MED Plant LCOW – Cogeneration Configuration with Tax Credit Adjustment**

*Investment = \$126,000,000*

*20 year CRF 5% = .08024*

*O&M = \$6,300*

*Energy = \$0*

*Annual Output = 36,500,000M<sup>3</sup>/year*

*Levelized cost of water =  $\frac{((\$126,000,000 \times .08024) + \$6,300 + \$0)}{36,500,000}$*

*LCOW = \$0.28/M<sup>3</sup>*

*LCOW with tax credit adjustment of \$.05/ M<sup>3</sup> = \$0.23*

---

<sup>34</sup> “American Recovery and Reinvestment Act” (ARRA)

With these types of policy driven adjustments we make it possible to create more useful efficiency in thermal plants and provide a way to get additional use of potentially carbon intensive energy for greater use and to create a method for zero added carbon desalination. There are multiple mechanisms, renewable energy credits, tax credits, and even punitive measures that can be used to motivate positive action. If measures are crafted to achieve a few basic functions of increasing fresh water, reducing carbon, and capturing greater combined efficiency, there may exist ways to grow desalination production with clean technologies.

### **Infrastructure Planning**

In addition to the basic economic incentives needed to propel the development of desalination plants using cogeneration, master planning policies are needed for ocean-front states. With the potential vulnerabilities of sea-level rise and extreme weather events that lead to flooding in oceanic regions, there is a need for intelligent planning to drive more resilient, accessible solutions for the distribution of industrial fresh water and protected storage to be strategically tied to the water distribution systems in municipalities. In addition, the federal government should be exploring the creation of aqueduct pipelines in parallel rights of way to oil and gas pipelines to move industrial fresh water supplies inward from the coast to other water stressed areas. In the following sections we can look to Texas and Israel as examples of successes in water distribution planning.

## **Texas**

Texas is home to 38 of the 250 desalination plants in the U.S. and is beginning to develop both ground water and seawater desalination plants parallel to the pipeline infrastructure. This includes a \$109.5 million desalination plant project being managed by the San Antonio Water Systems with Texas Water Development Board funding to build a ground plant, groundwater wells, and a pipeline to move the water supply to the people of San Antonio. The 2017 Texas State Water Plan looks at the complete range of activities in conservation, supply, and distribution to manage the growing distance between demand and reducing supplies.

In addressing the challenges and expenses of desalination and the required planning for infrastructure and budgeting, the report states, “The most expensive is seawater desalination, although this can vary greatly by individual project and depends on whether the unit costs still include debt service in any given decade. There can be a substantial range in unit costs even within a single type of strategy and between regions. For example, if a seawater desalination strategy requires a 100-mile pipeline inland, the costs of that strategy will likely be substantially greater than a seawater desalination plant built to serve an entity located on the coast.”<sup>35</sup>

Although Texas is providing only a small portion of its water through desalination plants, the plan provides a clear example of the importance of master planning policy and public investment in infrastructure to move fresh water from industrial fresh water sources to the water distribution grid.

---

<sup>35</sup> Texas Water Development Board, “2017 State Water Plan”, Page 99

## **Israel**

Since its founding in 1948, Israel has invested in innovative water management practices and technologies. Foreign and domestic policy has been shaped significantly by the need and for fresh water in one of the most water stressed places on the planet. Israel, the Palestinian Territories, Syria, Lebanon, and Jordan all have interest in access to the limited source of water and control over the Jordan River. In addition, conditions make it difficult—but not impossible—to sustain a good quality of life and economic prosperity. The soils in this area of the Middle East tend to be saline. There is also a limited fresh water source flowing out of the Jordan River. Israel began its search for solutions, not just in the territorial leverage of the river and other aquifers, but in reaching out to other water resources and applying technological solutions to produce fresh water. The challenge in doing so is to identify sources, establish best value methodologies for desalination, transport the water, manage distribution, and conserve the resource in its actual use.

Israel has a central water authority that evolved out of a consolidation of multiple agencies. The authority is responsible for the development and operation of the water infrastructure and conservation policy in the country. Like most water authorities, the Israeli authority is responsible for capture, distribution, sewage treatment, and reclamation. Israel leads the world in water technologies, which have helped the country overcome extreme poverty in 1948 to reach one of the highest standards of living in 2017. Though the country has done groundbreaking work in conservation and drip

irrigation, flattening the per-capita usage, the population has grown from 800,000 to 7.2 million. As a result, Israel has created taxes to control household consumption. The growing population in this region has created nearly a ten-fold demand increase in the life of the nation. This has required that Israel engage in the development of innovative desalination technologies and national infrastructure projects in water transportation.

International and transnational cooperation is where Israel shows another level of depth in the application of coordinated policy. As the population has grown, so has the demand for fresh water. Israel needs more ways to match demand volumes. Other sources that could be incorporated into this system include the Sea of Galilee, saline aquifers, and the Mediterranean. This is where the opportunity for cooperation comes into play.

The Israel-Jordan Treaty of Peace of 1994 and the Oslo II Accord of 1995 aspire to create an integrated solution. Allocations for the Galilee, Yarmuk River, and Jordan River were spelled out. Furthermore, access and protection of the aquifers were established to maintain the source and prevent water pollution. Both agreements aimed to alleviate water shortages through cooperative projects, both regional and international, and overcome the severe shortfall in supply.<sup>36</sup>

---

<sup>36</sup> Oslo II Accord





Figure 15 - Map Israeli - Jordanian Desalination and Pipeline Master Plan<sup>37</sup>

The Israeli-Jordanian agreement has shown great promise (Figure 15). The Israelis provided Jordan with approximately 50 MCM/yr. from the Sea of Galilee and 40MCM/yr. from the Red Sea. In addition, approximately 100 MCM/yr. of brackish brine is piped to the Dead Sea to slow the recession of that body. Israel received an additional 40 MCM/yr. from the Red Sea (across Jordanian land) and retained general management and control of the Jordan River aquifers. Israel's technology and management supplied the needs of both nations through shared lands. In 2015, the Israel Water Authority reported that natural water sources supplied 38 percent of the country's need from the Sea

<sup>37</sup> Jeremy Josephs, "Green Light for Red-Dead Sea Pipeline Project", Page 3

of Galilee (10 percent) and the aquifers (28 percent). Note that 62 percent of the water comes from manufactured processes including storm water (3 percent), brackish water (11 percent), sewage (21 percent) and seawater (27 percent). This demonstrates the tremendous role desalination will continue to play in reversing desertification, supplying the needs of a growing populous, and feeding economic prosperity and trade.<sup>38</sup>

The desalination plant that will be at the center of this endeavor will be the largest in the region. “The plant would have a capacity of 320 million M<sup>3</sup>/year at start up, rising to 850 M<sup>3</sup>/year by 2060. It would require 247 MW of power in 2020 and 556 MW in 2060. The post-desalination high-salinity water would be piped to the Dead Sea with a view to halting, and eventually reversing, its shrinkage. Furthermore, a hydroelectric plant would be built, supplying electricity to Jordan, Israel and the Palestinian Authority.”<sup>39</sup> Here also we can see where the next generation of integration of cogeneration technologies could turn this large power consumer into a total power natural or power plus project. Clearly the Israeli-Jordanian plan seeks to use the hydro-electric opportunities to create carbon-neutral benefits. Also, the strategic placement of the plant looks to create benefits for Israel, Jordan, and the Palestinian Territories.

Israel is continuing to push the technological boundaries on water conservation and rebuilding water supplies through everything from desalination to waste water reclamation processes. The country’s policy has been shaped around water management as a matter of survival since its founding as a nation. Israel demonstrates the application

---

<sup>38</sup> Seth Siegel, *Let There be Water: Israel’s solution for a water-starved world*, Page 252.

<sup>39</sup> Jeremy Josephs, “Green Light for Red-Dead Sea Pipeline Project”, Page 4

of all levels of policy to drive a successful water management plan. The Israeli application of the full dimension of policy allowed this nation to achieve access to sources seemingly out of reach. It further created a regional stabilization through transnational cooperation. Israel and Jordan will both be able to improve their agricultural and domestic water use. In an area of the world plagued by destabilizing forces, here water resources, policy, and technology intersect to create the opportunity for security and quality of life improvements.

Policy is the front line of shaping a society's approach to holistic water management. While we see the rise of desalination technologies and expanded usage as potentially market driven, government's role in creating more far-reaching and broadly integrative plans can help shape the application of innovative technologies beyond what the market alone will do. For the application of desalination without carbon impact, we rely on policy to help to shape efficiency in power plants, create incentives for industrially processed fresh water, and foster investments in water distribution infrastructure.

### **Industrial Onsite Desalination**

Where the possibility of infrastructure for water conveyance is cost prohibitive, there is also the idea of creating tax incentives for industrial onsite desalination to offset the industrial plant (or power plant) water use to be net zero. Looking at the fact that in the U.S. and other industrialized nations up to 40 percent of national water consumption is industrial, it could be relevant to just have these plants incentivized to produce their own water.

## **Part 7 – Conclusion**

Policy can be a powerful mechanism to draw together the state of the industry technologies in desalination and industrial cogeneration to create low carbon impact freshwater production to relieve water stress. We find a wealth of emerging state-of-the-art technologies in a variety of desalination techniques. In addition, heat engine technologies with the application of cogeneration (CHP) offer a variety of solutions for integrating processes that will permit net zero carbon desalination. While reverse osmosis plants have continued to emerge as the preferred technology in a stand-alone plant, there is opportunity to capture greater capacity if cogeneration thermal plants are also able to emerge. Required is policy that will shape the use of these technologies and facilitate the growth of water production through desalination. The policies should focus on the following key points:

- Increase production of desalination plants to offset the growing demand for water
- Create economic incentives for reduced carbon solutions for fresh water desalination
- Look for regulations to reduce heat pollution output
- Create tax incentives to reduce capital costs on cogeneration plants in combination with desalination plants
- Create infrastructure plan and public investment in water conveyance.

In several parts of this study, the levelized cost of water (LOCW) was calculated as we calculate the levelized cost of energy:

$$\text{Levelized cost of water} = \frac{((\text{Investment} \times \text{CRF}) + \text{O\&M} + \text{Energy Cost})}{\text{Annual water Output}}$$

Doing so, we saw the way in which policy would support cogeneration that can reduce the cost of water through a combination of efficiencies and supportive tax incentives. These types of policy mechanisms can lead the way to making better productive use of a portion of the 66 quadrillion Btu/year of wasted energy; increasing usable freshwater supply with energy where the carbon expenditures have already occurred. Policy mechanisms and public infrastructure planning must also be a part of making these systems part of the civil water supply network.

Shoreline and water stressed states in the U.S. should follow the best practices of countries like Israel to establish comprehensive plans that set forth a fully integrative strategy for water management. Such plans must include investment in desalination to fortify the replenishment of fresh water, offsetting the growing water demand. To avoid the carbon intensive/energy intensive qualities of current stand-alone thermal plants and filtration plants, a policy infrastructure should be created to drive combined heat and power (cogeneration) solutions and integration of renewable energy sources to create a carbon-neutral approach. As can be seen in the Texas water plan (Part 6), the amount of desalination plants required to offset the current divide between demand and supply is significant and drives the need for low carbon solutions. While we may associate these needs with the dry and sandy states of the Southwest or Midwest, the water demands of the densely populated, seemingly water-rich northeastern states are just as important to offset decreasing water supplies.

To help to curb the negative effects of waste heat ejection as a pollutant through potentially harmful effects on ecosystems, policy can be written to create controls around waste heat energy.

The ARRA created an income tax credit around CHP measured in terms of efficiency, which expired in January 2017. This is a good example of policy that can be leveraged to help facilitate investment in cogeneration for thermal desalination.

Government's role in policy is to offset significant capital costs through grants, tax credits, research and development tax incentives, and government funding. Low carbon industrial desalination can be made equivalent for renewable energy credits (RECs) and carbon credits in their respective markets.

While this study is focused on the intersection of policy and technologies to enhance water supply, it must be noted that the most successful integrated plans also focus on water conservation. In addition, plans must balance our concerns of getting water supplies to the human population with our ecological stewardship. Policy must cover the development of desalination plants, the mining and transportation of seawater, and the distribution of industrially manufactured fresh water to be joined with the existing water distribution and storage systems.

California is on the leading edge of developing laws and guidance for desalination plants to capture seawater and dispose of brine in a way that is sensitive to marine ecosystems. The Water Plan produced in 2015 included extensive guidance and provisions for the protection of marine life through intakes and requirements for impact analysis for disposal of brine.<sup>40</sup> Though these may appear to be obstacles for development of plants, they raise realistic concerns and shape the burden of responsibility to the developer of the plant to perform due diligence in the design, construction, and operation of plants.

To establish infrastructure for the mining of seawater, movement of brackish, brine, and industrial fresh water, and to manage demand for the public at large or dedicated customers through a variety of covenants, water authorities in states like Texas, California, and other shoreline states need to follow the comprehensive strategic vision of countries like Israel, where water management is not simply a municipal utility but a national economic driver.

There must be goals to create significant growth in low carbon industrial desalinated fresh water supplies. This can be done in new and retrofitted power plants through cogeneration arrangements. To do so, there will need to be policy and planning for building infrastructure to transport supplies of seawater and brackish from water sources (seawater and ground water) to the plants. Then, similar infrastructure is required from plants to the municipal water supply infrastructure or other dedicate users. In the century of the mega city, it will be both imperative and advantageous to build these utility

---

<sup>40</sup> State Water Resources Control Board, "California Ocean Plan"

infrastructures around urban centers. Because the density of human population appears to be growing toward cities, creating additional water supply infrastructure to the cities helps focus this supply on concentrated targets versus trying to build supply lines around a wide-reaching provincial approach.

### **Expected Outcomes**

Israel provides the clearest vision of how policy and innovation can effectively reshape a state's trajectory economically, ecologically, and socially. Through a comprehensive national policy and management plan, Israel went from a poor state in the most water stressed area of the world to a thriving state and economy where the desert is being farmed.

### **Mitigation**

Creating solutions for capturing new fresh water supplies through industrial fresh water desalination processes will play a significant role in mitigating the current state of the planet as our global fresh water supplies continue to be consumed at rates that exceed their natural replenishment rates. But we need to look beyond carbon intensive stand-alone processes and turn to cogeneration processes that result in net zero carbon additions and to renewable energy powered processes. Integrative planning can allow water stressed areas to follow Israel's example in reversing desertification. All these strategies have the potentials to help efforts in reducing or arresting anthropogenic planetary warming.



## **Adaptation and Resiliency**

Establishing a stronger freshwater infrastructure that mines the seemingly infinite supply of the planet's oceans and creates a conveyance infrastructure will make shoreline states in the U.S. more resilient to the effects of extreme weather events such as drought, earthquakes, super storms, and more.

## **Security**

Creating water independence and greater resource independence has a direct causal relationship to national security for nations in water stressed areas of the world. While security may not be a concern between California and Arizona, we can see countries like Bangladesh or the desert laden north-African countries use water management planning to enhance stability and security.

## **Future Outlook**

Policy will play a key role in establishing a productive framework for the enabling technological innovations in desalination and cogeneration to enhance the production of freshwater to overcome water-stress. It is the hope that water management strategies can play a key role in the long-range stability and prosperity of nations around the world.

Over the past century, national policy has been focused on strategic access to oil. In the 21<sup>st</sup> century, more focus will need to be turned to national, provincial, and municipal policies around fresh water. Seawater desalination is part of finding new sources for that water. Shaping policy to encourage low carbon, energy efficient, cogeneration, and renewable energy powered desalination with the support infrastructure for conveyance of

brackish, brine, and industrial fresh water will contribute to effective solutions and prosperity.

## Bibliography

1. Ali Al-Karaghoul n, Lawrence L. Kazmerski Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes, Sustainable Energy Reviews, Science Direct and theNational Renewable Energy Laboratory, Golden, CO 2012
2. Almar Water Solutions, “Desalination Technologies and Economics: CAPEX, OPEX & Technological Game Changers to Come”, Mediterranean Regional Technical Meeting, Marseille CMI, December 12-14, 2016
3. “American Recovery and Reinvestment Act” (ARRA) Washington DC, 2008
4. Mauro Capocelli,”Waste Heat Recovery in the Oil & Gas Sector”, University UCBM – Rome, 2013
5. Center for International Earth Science Information Network (CIESIN), Columbia University and Centro Internacional de Agricultura Tropical (CIAT), <http://sedac.ciesin.columbia.edu>, New York, 2017
6. Howard Chung and David Sunding, “Water Markets and Trading”, *The Scholarly Commons*, Cornell University School of Hotel Administration, New York, 2006
7. Heather Cooley, Matthew Heberger, “Key Issues for Seawater Desalination in California: Energy and Greenhouse Gas Emissions”, Pacific Institute, California, 2013
8. Tawfiq H. Dahdah, Alexander Mitsos , “Structural optimization of seaw ater desalination: II novel MED–MSF–TVC configurations”, *Desalination: The International Journal on the Science and Technology of Desalting and Water Purification*, Amsterdam, Elsevier B.V., Science Direct, 2017
9. M.A. Daheim, S.A. Sayed, O.A. Hamed, “Energy Analysis and Waste Heat Recovery in a Refinery”, Pergamon Journals, LTD, Great Britain, 1985
10. Ali M. El-Nashar, “Cogeneration for Power and Desalination: State of the Art Review”, *Desalination: The International Journal on the Science and Technology of Desalting and Water Purification*, Amsterdam, Elsevier B.V., Science Direct, 2017
11. Dr. Oded Eran, INSS; Gidon Bromberg, and Michal Milner, *The Water, Sanitation and Energy Crises in Gaza Humanitarian, Environmental and Geopolitical Implications With Recommendations for Immediate Measures*, Tel Aviv: INSS, 2014
12. EU Staff, “Water in the Israeli-Palestinian conflict”, *European Parliament Briefing 2016*, Geneva: European Union, 2016.
13. General Electric, “US Patent 8545681 B2”, US Patent Office, Washington DC, 2013
14. Herbert Hoover, W.S. Norviel, W. F Mclure, Delph E Carpenter, J. G. Scrugham, Sephen G. Davis Jr, R. E. Caldwell, Frank C. Emerson, “Colorado River Compact”, City of Santa Fe, New Mexico, 1922.
15. Soteris A. Kalogirou, “Concentrating solar power plants for electricity and desalinated water production”, World Renewable Energy Congress; Sweden, 2011

16. Andrew Hodges, Kristiana Hansen, Donald McLeod, "The Economics of Bulk Water Transport in Southern California" Department of Agricultural and Applied Economics, University of Wyoming, Laramie, WY, 2014
17. Rowan Jacobsen, *How a New Source of Water is Helping Reduce Conflict in the Middle East*, Ensia, St Paul, MN: Ensia, July, 19, 2016
18. Matt Jenkins "The water czar who reshaped Colorado River politics" *High Country News*, Denver March 2, 2015
19. Jeremy Josephs, "Green Light for Red-Dead Sea Pipeline Project", Water and Waste Water International, Israel, 2016
20. Lawrence Livermore National Laboratory, LLNL.gov
21. Wu Lianying, Hu Yangdong, Gao Congjie , "Optim um design of cogeneration for power and desalination to satisfy the demand of water and power", *Desalination: The International Journal on the Science and Technology of Desalting and Water Purification*, Amsterdam, Elsevier B.V., Science Direct, 2017
22. Margaret McKenzie, "Water Technologies and Potential Cooperation along the Jordan River Basin", *UN Global Sustainable Development 2014 Prototype Edition*, New York: UN, March 2014
23. Rezaei, A. Naserbeagi, Gh. Alahyarizade, M. Aghaie "Economic evaluation of Qeshm island MED-desalination plant coupling with different energy sources including fossils and nuclear power plants" *Desalination: The International Journal on the Science and Technology of Desalting and Water Purification*, Amsterdam, Elsevier B.V., Science Direct, 2017
24. A. Richey, B. Thomas, M.H. Lo, J. Reager, J. Familglietti, K. Voss, S. Sensen, and M. Todell, "Quantifying Renewable Groundwater Stress with GRACE" *Water Resources Research* *Agü Journal*, Wiley, New Jersey, 2015
25. Mohammed Saleh Al. Ansari, "Concentrating Solar Power to Be U sed in Seawater Desalination within the Gulf Cooperation Council", *Energy and Environment Research; Vol. 3, No. 1*; Canadian Center of Science and Education, Canada 2013
26. Seth Siegel, *Let There be Water: Israel's solution for a water-starved world*, New York: Thomas Dunn Books/St. Martin's Press, 2015
27. Mahmoud Shatat and Saffa B. Riffat , "Water desalination technologies utilizing conventional and renewable energy sources", Institute of Sustainable Energy Technology, University of Nottingham, Nottingham, UK, 2012
28. State Water Resources Control Board, "California Ocean Plan", State Water Resources Control Board, California Environmental Protection Agency, California, 2015
29. Texas Water Development Board, "2017 State Water Plan", Texas, 2017
30. Crystal Thompson and CRWUA Staff, "Law of the River", Colorado River Water Users Association, Las Vegas NV, 2017
31. *The Helsinki Rules on the Uses of the Waters of International Rivers*, London: International Law Association, 1967
32. John Tonner, "Potential for thermal desalination in Texas", Texas Water Development Board, Austin, 2004
33. Transnational Institute, *Water Management Challenges in Palestine*, Palestine:

TNI 2008

34. UN Staff, “Water resources ‘a reason for cooperation, not conflict’, Ban tells Security Council”, *United Nations News Centre*, New York: UN News Centre November 22, 2016
35. Water Authority, State of Israel, *The Issue of Water between Israel and the Palestinians*, Tel Aviv: Water Authority State of Israel, March 2009
36. Catherine Weibel & Sajy Elmughanni, *Water and Energy Crisis in Gaza: Seeking a multi-stakeholder partnership for solutions*, Palestine: UNICEF State of Palestine, 2014
37. Nikolay Voutchkov, *Desalination Engineering: Planning and Design*, New York: McGraw Hill 2013
38. Nikolay Voutchkov, “Energy use for membrane seawater desalination – current status and trends”, *Desalination: The International Journal on the Science and Technology of Desalting and Water Purification*, Amsterdam, Elsevier B.V., Science Direct, 2017
39. “Annex III Protocol Concerning Civil Affairs,” *The Israeli-Palestinian Interim Agreement (Oslo II)*, Washington DC, September 28, 1995
40. US Department of the Interior “Colorado River Basin Supply and Demand Study”, US Department of the Interior, Washington DC, 2012
41. US Energy Information Agency, EIA.org
42. Klaas Visser, “Waste Heat Recovery for Desalination from Steam Power Plants”, *Water Online*, KAV Consultants Pty Ltd, Pennsylvania, April 17, 2014
43. <https://data.worldbank.org>
44. World Water Council “The Use of Water Today”, France, 2000, Chapter 2